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THE ASTROPHYSICAL JOURNAL

AN INTERNATIONAL REVIEW OF SPECTROSCOPY AND ASTRONOMICAL PHYSICS

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OCTOBER 1930

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AN INTERNATIONAL REVIEW OF SPECTROSCOPY AND ASTRONOMICAL PHYSICS

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NEW ULTRA-VIOLET SPECTRUM OF HELIUM[1]

By JOHN J. HOPFIELD

ABSTRACT

The *resonance series of helium in the ultra-violet has been extended to ten members.* Some of the lines have been measured in orders as high as the fifth and with considerable accuracy.

Continuous bands have been found superimposed upon atomic lines. Because of these bands the first two lines of the resonance series appear very broad and asymmetrically self-reversed at 1-mm pressure.

Intense continuous spectra of molecular origin have been discovered in the region between λ 500 and λ 1125. This is the only strong continuous spectrum that has yet been found in the region λλ 500–900. To account for the observed facts *two distinct* species of *helium molecules are postulated.*

The first *absorption spectra* to be obtained in the region λλ 500–900 *are recorded.* These are shown for O_2 and H_2.

INTRODUCTION

The spectrum of helium in the extreme ultra-violet was first investigated by T. Lyman.[2] He found the resonance series of helium and correlated it with its visible counterpart. This resonance series has a continuous emission spectrum beginning near the head of the series and extending toward shorter wave-lengths. He observed also an intercombination line at λ 591 and a line at λ 600. Other than this investigation and a modification of it by L. A. Sommer, there has appeared very recently an important article by P. G. Kruger[3] working with Professor Paschen in Berlin. Kruger verified the in-

[1] A preliminary report of this work was given in a letter to the *Physical Review*, **35**, 1133, 1930, and it was later reported at the Eugene meeting of the American Physical Society (*ibid.*, **36**, 784, 1930).

[2] *Astrophysical Journal*, **60**, 1, 1924.

[3] *Physical Review*, **36**, 855, 1930.

tercombination line λ 600 of Lyman, and the λ 600 band of Sommer, discovered two new lines ascribed to a double electronic transition in helium, and greatly extended the resonance series of *He* II.

The investigation leading to this paper was originally planned with the object of observing the effect of the presence of helium on the appearance of other ultra-violet spectra. This primary object has been accomplished in part with mixtures of helium with the gases hydrogen, oxygen, nitrogen, and carbon dioxide.[1] As often happens in scientific work, the by-product of the search has proved to be of as great interest as the original problem, and has perhaps even greater usefulness in physical research. This paper is devoted entirely to the new spectra of helium.

It is well known that helium, although ordinarily a monatomic gas, forms molecular helium under certain conditions of excitation in discharge tubes. Many workers have studied the visible spectrum of molecular helium, but it appears that similar conditions of excitation in the extreme ultra-violet had not previously been investigated.

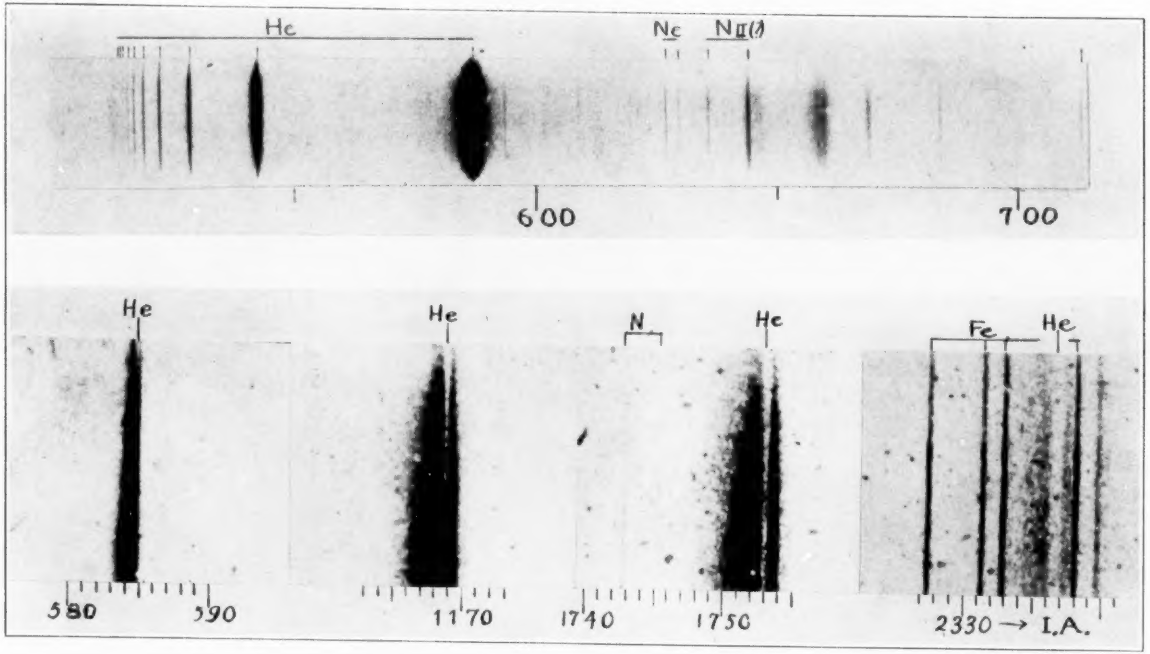
APPARATUS

A vacuum grating spectrograph containing a lightly ruled speculum metal grating of 50-cm radius of curvature was used. It contained 1180 lines per centimeter and was ruled at Johns Hopkins University. The dispersion in the first order was about 16.7 A per millimeter. The plates employed were commercial Schumann films purchased from Adam Hilger & Company, London.

The discharge tube was Π-shaped with a total length of about 1 m and about 1 cm internal diameter. The electrodes were in the depending ends of the tube, and the horizontal portion faced the slit end-on. A novel feature of this was a heavy glass capillary of about 1-mm bore and several centimeters long built on to the end of the main tube and close to the slit. Two separate pumping systems were maintained. Each system contained a mercury condensation pump and an oil force-pump. The mercury traps in the line were cooled with liquid air. One such system pumped from the discharge side of the slit and the other from the receiver side. When a flowing gas was

[1] Hopfield, *ibid.*, **35**, 1133, 1930; *ibid.*, **36**, 789 (Abstract 22), 1930; *ibid.* (Abstract 23), 1930; *ibid.*, **35**, 1586, 1930.

PLATE VI



1

2

LINE SPECTRUM OF HELIUM

1.—Resonance series, continuous spectrum absent.

2.—Resonance line λ 584, in first, second, third, and fourth orders asymmetrically reversed.

used, this arrangement maintained a fairly large difference of pressure between the discharge tube and the receiver, and helped to eliminate much of the undesirable light-absorption to which even a small trace of a foreign gas gives rise in this region. Furthermore, the glass capillary formed a good electrical resistance and kept the discharge out of the receiver and thus prevented fogging of the plate. At the same time, on account of the high reflectivity of glass for ultra-violet light when it strikes at a grazing angle, the aperture of the grating was not appreciably diminished. The horizontal part of the discharge tube contained a quartz window at the end farthest from the slit. This allowed the use of the iron arc comparison spectrum for a part of the region photographed.

Torsion, capillary valves of glass allowed the gases used to stream through either the discharge tube or receiver or both at any desired rate. The rest of the equipment consisted of the transformers, condensers, spark gaps, etc., needed to meet the requirements of the experiments. The hydrogen and oxygen were generated electrolytically and dried with phosphorous pentoxide. The helium, which was generously supplied by the United States government, was further purified for spectroscopic purposes by passing it slowly through absorbing charcoal contained in traps immersed in liquid air.

DESCRIPTION OF PLATES

Plate VI, No. 1, shows the line spectrum of helium in the first order. The helium in the discharge tube and the receiver was at a very low pressure, and an oscillatory discharge was used. The wave-lengths, the approximate intensities, and the orders of the spectrum in which the various lines were measured are given in Table I. When the wave-lengths are obtained from spectra in more than one order, the higher orders are given more weight in the evaluation of the wave-length. The calculation of the deepest term of *He* I was made by using the known values of the 2^1P-, 3^1P-, and 4^1P-terms in connection with the wave-lengths obtained for the first three lines of the resonance series. The three wave-lengths were given slightly different weights in getting the average value of this deepest 1^1S-term. That this value is well chosen and that the wave-lengths are fairly accurate is shown in column 5, which gives the differences be-

tween the observed values and those computed with the 1^1S-term as found above and the values of the known n^1P-terms as bases. Ten lines of the 1^1S-n^1P series were obtained, this being three more than were measured by Lyman. The very large gradient of intensity for some of the lines of this series is remarkable, and is due, I think, in part to the reduced reflecting power of the grating in this region of short waves. This is treated more fully in a later paragraph. The intercombination line λ 591, also recognized by Lyman, is of moderate intensity. The lines are all sharply focused, and the broadening

TABLE I

HELIUM LINES

Wave-Length I.A. Vac.	*I*	ν Cm^{-1}	Series Designation	λ Obs. $-\lambda$ Cal.	Orders of Spectrum Measured
591.406	13	169,088.5	1^1S-2^3P	0.009	2,3,4
584.328	88	171,136.7	1^1S-2^1P	.008	2,3,4
537.014	44	186,214.9	1^1S-3^1P	−.003	2,3,4,5
522.186	22	191,502.6	1^1S-4^1P	−.015	2,3,4
515.596	20.6	193,950.3	1^1S-5^1P	−.009	2
512.07	18.5	195,286	1^1S-6^1P	−.017	1
509.97	14.5	196,090	1^1S-7^1P	−.015	1
508.63	10.0	196,607	1^1S-8^1P	−.001	1
507.71	6.0	196,963	1^1S-9^1P	.003	1
507.08	5.2	197,208	1^1S-10^1P	.035	1
506.56	5.0	197,410	1^1S-11^1P	0.003	1

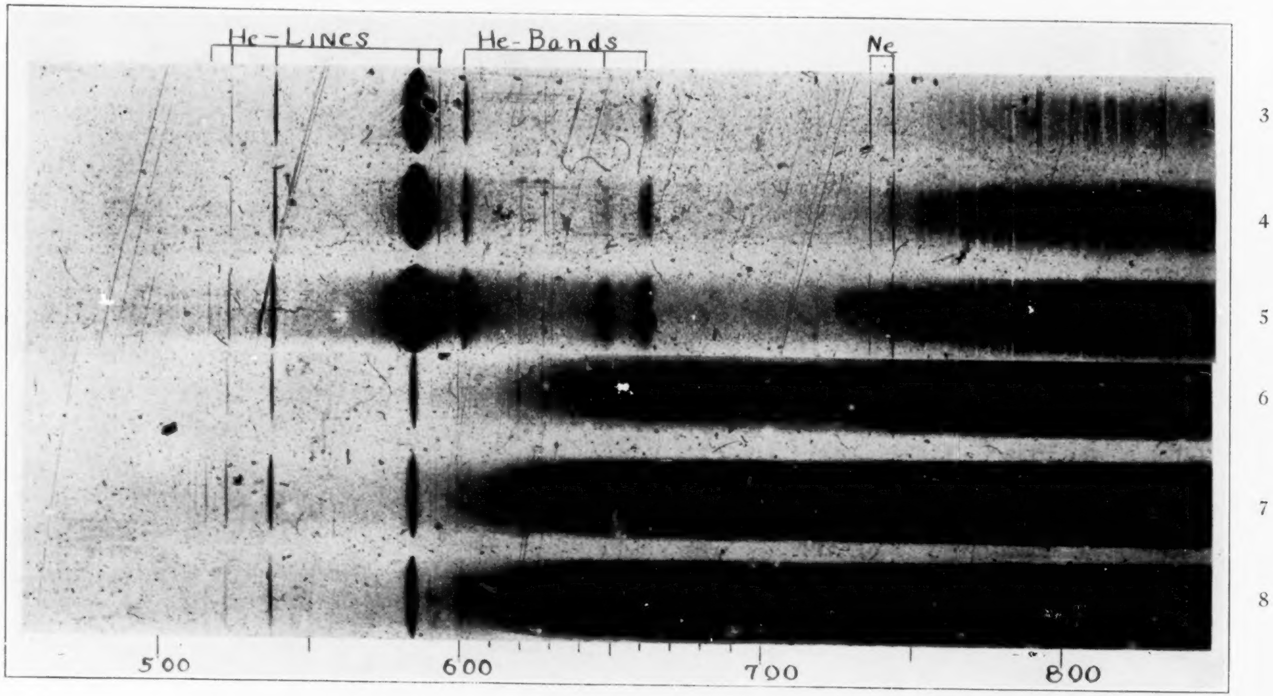
Spectroscopic constants of the helium atom: 198,314.4 ± 5 cm^{-1}, deepest term; 24,465 volts, ionizing potential of the atom; 21,112 volts (λ 584.328), first resonance potential.

Weak resonance lines: 20,518 volts (λ 601.418) from the 1^1S-2^1S line of Kruger (*loc. cit.*); 20,859 volts (λ 591.406) for the line 1^1S-2^3P of Lyman (*loc. cit.*); 19,726 volts, 2^3S metastable state.

observed in the first two is due in this case to the enormous intensity and consequent overexposure of the lines. The density of the lines was estimated from microphotometer curves of this spectrum. The continuous spectrum observed by Lyman at the head of the series is barely noticeable in the present instance, and the new continuous spectra, seen in the pictures to be described presently, are absent under the low pressure under which this spectrogram was taken.

Spectrum No. 2, Plate VI, shows the resonance line of helium as obtained self-reversed in four orders. The fourth order of this line is shown with the first-order iron comparison spectrum. The most

PLATE VII



HELIUM SPECTRA

3, 4, 5.—Helium bands near λ 600
6, 7, 8.—Continuous spectrum of helium

prominent feature of this line, although the time of exposure was very short, is that the line is very broad and asymmetrically self-reversed. One might at first sight attribute this broadening to a Stark effect, but the Stark effect gives symmetrical broadening. The second-order spectrum is stronger than the first, which shows an interesting characteristic of the grating.

Curve No. 9, Plate X, taken with the Zeiss recording microphotometer of this department, shows the distribution of intensity of λ 584 in the four orders. The broadness of the line, the asymmetry, and the direction of degradation are clearly shown. The second line

TABLE II

HELIUM BANDS

λ I.A. Vac.	I	ν Cm^{-1}	Shading	Series Designation	Remarks
664.30		150,534	To ultra-violet		Start
662.11	6.6	151,032			Maximum
661.30	7.0	151,217			Maximum
649.49	5.6	153,967	Uncertain		Maximum
648.08	5.2	154,302			
604.87	4.5	165,325			Maximum
602.700	7.5	165,920	To red	1^1S-2^1S	Maximum
600.409	11.0	166,553			
598.74	5.0	167,017			Maximum (?)
584.8	10	171,000	To ultra-violet	1^1S-2^1P	Head
537.2	5	186,150	To ultra-violet	1^1S-3^1P	Near middle

of the series, λ 537, shows asymmetrical self-reversal and also traces of a second minimum on the side of the shorter wave-length from the first minimum. In this case it appears almost as if the one minimum might be attributed to band absorption and the second to the self-reversal of the λ 537 line. The bands near the first and second lines of the resonance series of helium are most easily obtained at relatively high helium pressure in the receiver of the spectrograph and discharge tube and when an arc discharge is used.

Spectra 3, 4, 5 and 6, 7, 8 of Plate VII are pictures taken with two different types of discharge in helium. The first three are with the arc discharge and with varying times of exposure, while the last three represent varying exposure times and oscillatory discharge.

The pressure of helium in all six cases was alike and between 1 and 1.5 mm. The six spectra were taken on the same film. A film ordinarily contained nine pictures. The intermediate three were merely modified repetitions of some of these and were cut out to save space.

TABLE III

STANDARDS FOR MEASUREMENT OF HELIUM LINES

λ I.A. Vac.	Material	Orders Used	Reference
833.326	O II	1	*a*
937.812	*H*	1, 2	*b*
949.752	*H*	1, 2	*b*
972.546	*H*	1, 2, 3	*b*
1134.987	*N* I	1, 2	*a*
1200.681	*N* I	1, 2	*a*
1215.682	*H*	1, 2	*b*
1492.83	*N* I	1	*a*
1561.378	*C* I	1	*a*
1656.27	*C* I	1	*a*
1742.749	*N* I	1	*c*
2537.282	*Hg* I	1	....
2829.89	*He* I	1	....
2917.638	*He* I	1	....
2327.382	*Fe*	1	*d*
2331.300	*Fe*	1	*d*
2332.791	*Fe*	1	*d*
2338.007	*Fe*	1	*d*
2339.54	*Fe*	1	*d*
515.596	*He* I	1	*e*
522.186	*He* I	1	*e*
591.406	*He* I	1	*e*

a) Taken from tables published by MacInnes and Boyce.

b) Calculated theoretical values.

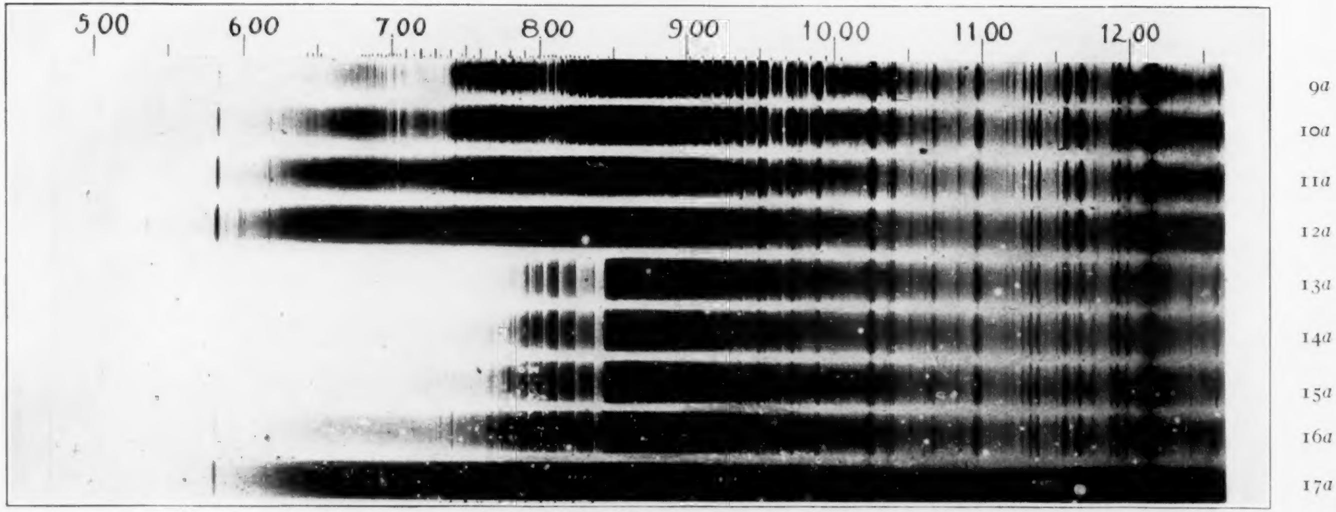
c) From unpublished work of the author, and measured in the third order of a 3-m vacuum grating spectrograph with iron standards.

d) Best values deduced from Kayser's *Tabelle der Hauptlinien der Elemente*.

e) Secondary standards established in the present work.

Numbers 3, 4, and 5 show some distinct continuous maxima or bands at λλ 600, 649, and 662, and also a continuous spectrum, which I shall call the "first continuous spectrum," sets in at λ 662, the first maximum, and extends toward shorter wave-lengths at least as far as λ 537. These continuous maxima and the band λ 600 have already

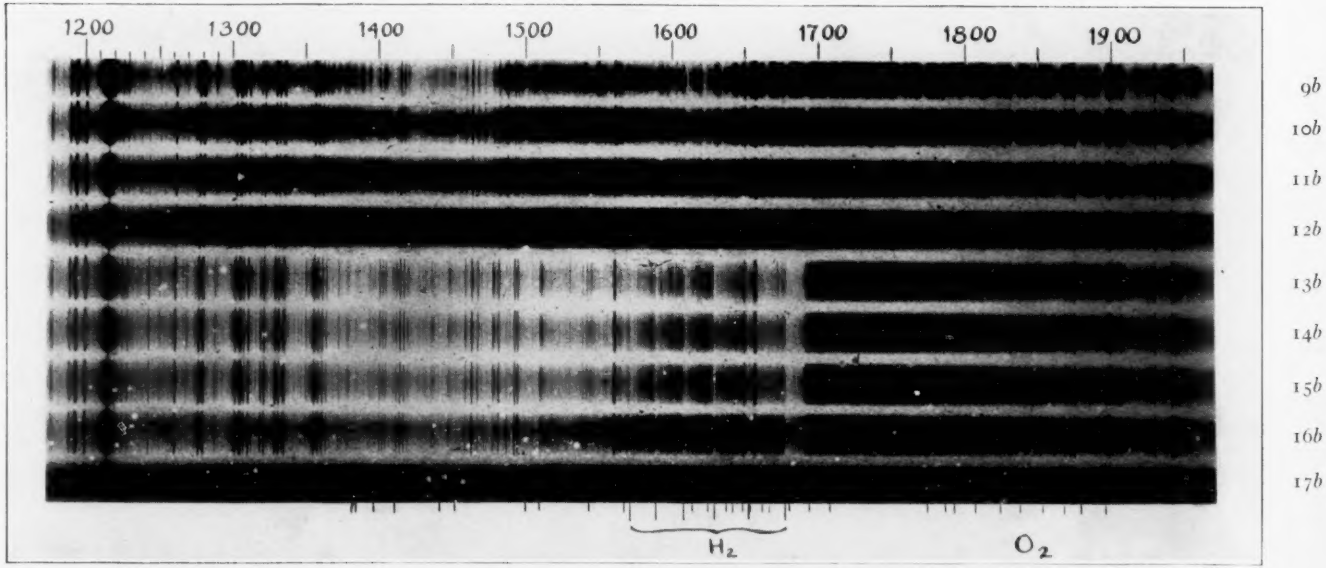
PLATE VIII



CONTINUOUS SPECTRUM OF HELIUM

9a–12a.—Oxygen absorption, λ 600–λ 1000
13a–17a.—Hydrogen absorption, λ 600–λ 850

PLATE IX



CONTINUOUS SPECTRUM OF HELIUM, SECOND ORDER

9b–12b.—Oxygen absorption, second order
13b–17b.—Hydrogen absorption, second order

been observed by Sommer,[1] and this part of the present work confirms his investigation. The correctness of his designation of the λ 600 band as being due to the 1^1S-2^1S transition is, however, open to question and will be more fully discussed farther on. As has already been remarked, the λ 600 band has recently been confirmed by Kruger,[2] who also finds the corresponding atomic line with it. The resonance line is enormously strong in comparison with λ 537.

Curve 8, Plate X, is a record of spectrum 5. It shows the faint continuous spectrum starting at λ 662, the continuous maxima, and the directions of degradation of these. The band λ 600 and the intercombination line λ 591 are prominent. The new continuous spectrum, which I shall call the "second continuous spectrum," begins to show in the present case at λ 750 and extends with increasing intensity toward the red. Visual observations of the discharge directly and with the aid of a spectroscope when these spectra were being taken show the characteristic yellow color of the arc discharge in helium, and in the spectroscope one observes the strong lines of *He* I. Traces of the visible bands of helium were also present.

Spectra 6, 7, and 8 of Plate VII, taken with an oscillatory discharge, show λ 584 much weakened in comparison with the higher lines of the series, and therefore a much more nearly normal distribution of intensities exists among the lines. On the other hand, the continuous maxima, the bands near the resonance lines, and the first continuous spectrum mentioned above have almost completely disappeared, while the second continuous spectrum has grown manifold in intensity and completely covers the background from λ 1125 (not shown in this picture) to the resonance line or beyond. The discharge in this case was of the peach color characteristic of the discharge in helium when the bands are prominent, and observations with the spectroscope showed that the helium bands were very strong and the atomic spectrum of helium very weak.

Spectra 9*a*, 10*a* . . . . 17*a* of Plate VIII and their extensions into the second order 9*b* . . . . 17*b* of Plate IX are enlargements made from the nine exposures taken on a single spectrum plate. The first four spectrograms picture the absorption spectrum of oxygen at various pressures, the top picture recording the spectrum with the high-

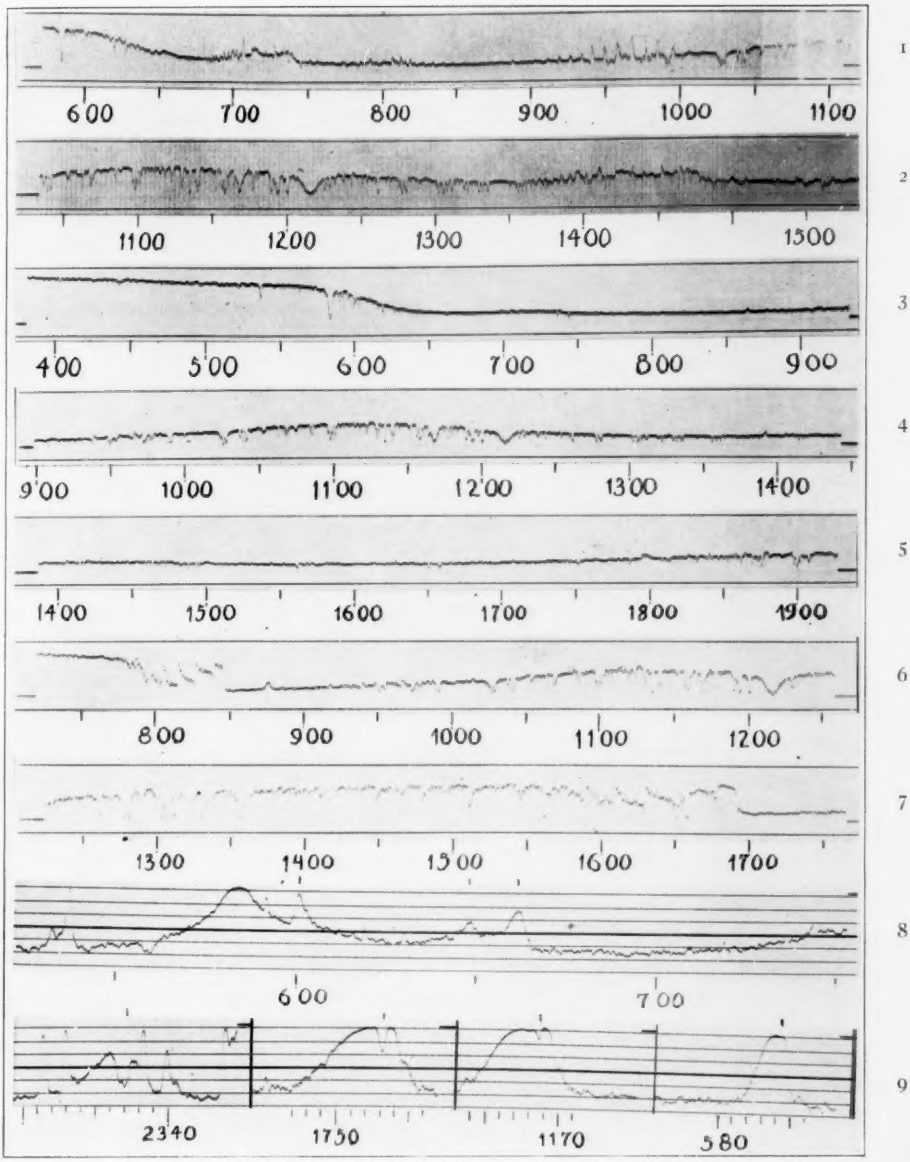
[1] *Proceedings of the National Academy of Sciences*, **13**, 213, 1927. [2] *Loc. cit.*

est oxygen pressure. The partial pressure of the oxygen was not measured, but it was not more than a few thousandths of a millimeter of mercury in any case. These indicate the extreme opacity of oxygen in this region of short wave-lengths. The next five pictures, 13–17, are corresponding spectra in the first and second orders of the absorption of hydrogen in this region. In these also the partial pressure of hydrogen was extremely small. This shows once more the extreme opacity of hydrogen in the region below λ 900. In fact, hydrogen is even more opaque than oxygen between λ 900 and λ 500. The opacity of both gases apparently rises as one approaches still shorter wave-lengths. This observation has important bearing on the extent of the continuous spectrum of helium, and will be referred to again in the course of this paper. As far as I know, this is the only strong continuous emission spectrum yet found in the region λλ 500–900, and consequently the foregoing absorption spectra are the first to be recorded in this region. These absorption pictures point out the utility of the new continuous spectrum for studying absorption spectra in this region. This range of the spectrum is rather a critical one with most molecules, since their higher excitations and even ionizing potentials occur in the space between 500 and 900 A. Furthermore, the observation of these discrete line- and band-absorption spectra proves beyond all doubt that we are dealing with a strong continuous background and not plate fog due to the active gases or scattered light in the receiver. The oxygen-absorption pictures shown here have not yet been measured. The hydrogen-absorption bands, so clearly recorded in the first and second orders, have been reported in a letter to *Nature*.[1]

Curves 1 and 2, Plate X, are taken from spectrum 10*a*, *b*, and show the absorption bands of oxygen (upward) and the emission lines and the continuous spectrum (downward). The curves and the spectra are supplied with a wave-length scale, and in many cases a finer one is drawn which the reader may extend if desired for interpolation. Most of the curves of intensity are also supplied at the ends with short, horizontal reference lines which register total blackness. This device also checks up on any shift of the zero-reading of the fiber of the microphotometer during successive runs.

[1] Hopfield, *op. cit.*, **125**, 927, June, 1930.

PLATE X



MICROPHOTOMETER CURVES OF THE HELIUM SPECTRUM

1, 2.—Continuous spectrum of *He* with absorption by O_2.

3, 4, 5.—Continuous spectrum of *He* with least absorbing gas.

6.—Continuous spectrum of *He*, with absorption by H_2, first order.

7.—Continuous spectrum of *He*, with absorption by H_2, second order.

8.—Helium bands near λ 600.

9.—Helium line λ 584 asymmetrically self-reversed, first, second, third, and fourth orders.

Curves 3, 4, and 5 of Plate X, from spectrum 12*a*, *b*, which was taken under very favorable conditions of helium purity and minimum leak in the receiver, show the second continuous spectrum gradually rising in intensity from λ 400 to λ 584. It then rises more rapidly and becomes horizontal at λ 560, where its intensity is about as great as that of the resonance line of helium. There seems to be a second rise at λ 740. Oxygen absorption is greater below this point, and this rise is apparently due to diminished absorption. At λ 900 a gradual diminution begins and a minimum is reached at λ 1125. At about this point the spectrum of the second order begins with considerable intensity and the curve rises again. The continuous spectrum is almost undisturbed by emission lines in the region λλ 584–900, and since it is extremely strong and uniform, most of these pictures being taken with ten minutes' exposure or less, it forms an excellent background for observing absorption spectra.

Curves 6 and 7 were taken from spectrum 13*a*, *b*. They were made in order to find the red limit of the continuous spectrum. It may be observed that although a minimum occurs at λ 1150, even here there is considerable light, and that the curve, after a slight rise, sinks again to a lower minimum at λ 1500. Shortly after this point the second-order spectrum sets in. The red limit of this spectrum is therefore not clear cut enough to make its determination easy. It is evident, moreover, that no sharp limit or discontinuity exists. The ensemble of plates and curves shows that the continuous background can be used in the second and in some cases even in higher orders for the observation of absorption spectra.

From the foregoing description of spectra and curves and the conditions under which the various spectra were obtained it is evident that the resonance lines are accompanied by seemingly continuous bands which practically coincide with them in position. These bands seem to be produced under conditions which bring out the first continuous spectrum and the maxima noted by Lyman[1] and Sommer.[2] This would indicate atomic binding in the helium molecule similar to that found in the mercury molecule, which produces the well-known bands near its resonance lines. A simple explanation might be that two helium atoms, under the relative high pressure used,

[1] *Loc. cit.* [2] *Loc. cit.*

unite loosely to form the molecule, and while they are thus joined, one of the electrons is excited either photo-electrically or by electronic impact to one of the higher molecular electronic states, say 2^1S, 2^1P, 3^1S, 3^1P, etc. One can assume, as in the case of mercury, that the electronic levels of the molecule of helium and of the normal helium atom nearly coincide, so that the bands and lines respectively are practically superimposed, as is actually the case. The band λ 600 found by Sommer[1] and those near λ 584 and λ 537 would then be designated as the 1^1S-2^1S, 1^1S-2^1P, and 1^1S-3^1P bands, respectively. In this regard the present work would seem to verify and extend the work of Sommer and also his assumptions as to the designation of the band λ 600. One can assume also that the helium atoms, or at least one of them, are first excited to the states 2^1S, 2^1P, etc., and that an unexcited atom may join with an excited one to form the molecule, and later emit these bands. Various difficulties arise as to the lifetime of the atoms in these excited states. A third assumption usually current is that the excitation is to one of the metastable states of atomic helium. The union of such a molecule with a normal one and subsequent radiation gives rise to the foregoing bands.

The second and more prominent continuous spectrum is already noticeable at λ 500 and extends at least to λ 1150. It appears only when the helium bands in the visible are present, and, therefore, it must be closely associated with them. In fact, the simplest condition for its best production is to set up the optimum conditions for the visible bands. When the conditions are such that these bands are absent, then the continuous spectrum cannot be observed. It has been observed long ago that relatively high pressures of helium and an oscillatory discharge promote the occurrence of the visible bands, hence the new continuous spectrum is likewise easily excited. If one uses a too-energetic spark discharge the bands are absent and the continuous spectrum does not appear.

Summarizing the experimental facts, it thus appears that the helium molecule has two types of spectra. The first consists of a limited continuous spectrum and the associated ultra-violet bands, some of which are superimposed upon atomic lines. This spectrum is

[1] *Ibid.*

developed under relatively mild conditions of excitation. The second spectrum consists of the visible bands of helium and the associated second continuous spectrum in the extreme ultra-violet. These are developed together under conditions of more vigorous excitation which apparently suppress the first spectrum.

DISCUSSION

One might propose, then, that since helium has two quite different and apparently unrelated band spectra, these arise from two quite different forms of the helium molecule.[1] Sommer,[2] to be sure, by extrapolation to the level 1^1S has correlated one of the ultra-violet bands, λ 600, with one of the known electronic levels of the visible band systems. Do the conditions under which these ultra-violet bands appear warrant this correlation? One would expect that they should be strongly developed in such case under the same conditions of excitation. This, I have already shown, is not true. Unfortunately, Sommer does not record any simultaneous observations of the character of the visible spectrum when the ultra-violet bands appeared. It would be an interesting and worth-while study to investigate the conditions of these dual spectra of helium with greater attention to the details of their production.

In the rather dim light of the experimental conditions and the known facts concerning atomic and molecular spectra of helium one might postulate two forms of the helium molecule, both neutral, to be sure, but differing widely in the energy of their lowest stable states. The one type of molecule, which for convenience of discussion I shall call A, is made of loosely bound, practically unexcited atoms. The molecule would be similar to that of mercury and the bands would be closely associated with the resonance lines and lines of lowest energy. The other type, B, would be made by the union of two atoms, one or both of which are excited to the 2^3S metastable state. This resembles the current theory. The last type is the source of the visible bands and of the second continuous spectrum. The

[1] For the purpose of this discussion the two types of helium molecules which give rise to the triplet and singlet band systems (W. E. Curtis, *Report on Molecular Spectra* [Faraday Society], p. 694, Sept., 1929) in the visible are included in one form of molecule.

[2] *Loc. cit.*

foregoing hypothesis suggests at once that each of the two types of molecule would have its own manifold of electronic energy-levels which would be quite independent of those of the other. One would hardly be justified in relating the ultra-violet bands of type A with the visible bands of B. In fact, this correlation of Sommer seems only to fit the one band λ 600 for which it was framed. The other strong bands predicted on the basis of his theory do not occur. The present hypothesis circumvents the difficulties met by him but introduces the type-A molecule. The three bands λ 537, λ 584, and λ 600 are then perfectly accounted for as existing near the corresponding atomic lines. A difficulty remains in that the continuous maxima at λ 648 and λ 662 are not associated with known helium lines, and the first continuous spectrum has not yet been accounted for.

The second continuous spectrum being associated with the visible bands must be of molecular origin quite analogous to the molecular continuous spectrum of hydrogen.[1] The molecule of type B, on being further excited by either radiation or electronic impact, is enabled to radiate the visible bands. The second continuous spectrum results when some configuration enables the molecule to break through the stable state of type B to an unstable lower state. On doing this it immediately dissociates emitting about 39.4 volts of radiant energy if both electrons are concerned in the transition, and 19.7 volts if only one electron is concerned. The assumption of the double electron jump would place the limit of the continuous spectrum near λ 300, and the continuous extension of this spectrum toward the red is due to the non-quantized kinetic energy subtracted from the foregoing amount by the unbound atoms. If only one electron were concerned in the readjustment and 19.7 volts of energy were available, the continuous spectrum should begin near λ 600, which on some of the pictures seems actually to be the case.

I am aware of the outstanding difficulty of accounting for the great intensity of the second continuous spectrum on the assumption of two excited atoms joining to form the molecule. It is almost certain, under the experimental conditions, that the normal atoms far

[1] J. G. Winans and E. C. G. Steuckelberg, *Proceedings of the National Academy of Science*, **14**, 867, 1928.

outnumber the excited ones, and therefore the probability of collision of two excited atoms is much smaller than that of a collision of a normal atom with an excited one. If the second continuous spectrum really begins in the neighborhood of λ 300, one can still account for it on the basis of the molecule formed of a normal and an excited atom if the one atom has double electronic excitation. The recent work of Kruger[1] would indicate the possibility of this process. It does not seem worth while to speculate further on the origin of this spectrum until its limits and intensity distribution are more fully known.

Outstanding difficulties exist to this study in the present experiments. It is hard because of the nearly normal mounting of the grating to get high reflecting power below λ 600, and apparently gases of impurities absorb strongly in this region to further weaken the spectrum. The very small intensity of the higher lines of the helium series and the almost complete absence of the continuous spectrum found by Lyman at the head of the series seem to indicate this. It would be interesting to study the new continuous spectrum with the grating, and preferably a glass one, mounted at a grazing angle to the light and with an exceedingly tight vacuum spectrograph.

An interesting question now arises in relation to the new continuous spectrum of helium. For instance, does it exist in the nebulae or fixed stars? Of course it is impossible to obtain ultra-violet evidence of this, so that one can judge only by the accompanying bands in the visible. So far as I know no helium bands have been found in stellar spectra.[2]

The calculations incident to this work have been greatly facilitated by the use of an electric computing machine, purchased by Professor R. T. Birge by a grant from the National Research Council and kindly placed at the disposal of the writer.

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September 18, 1930

[1] *Loc. cit.*

[2] O. Struve and A. Cristy, *Astrophysical Journal*, **61**, 277, 1930.

HEIGHTS IN THE CHROMOSPHERE

By S. A. MITCHELL

ABSTRACT

Heights above the photosphere are of the utmost importance in the interpretation of many solar and stellar phenomena. It is now generally agreed that in the sun a spectral line of Rowland intensity 10 takes its origin at a greater "effective height" than a line of less intensity 4. Four independent lines of investigation, mainly developed at Mount Wilson, must be considered as a proof: (1) solar rotation by spectroscopic methods, (2) the Evershed effect in sunspots, (3) the relativity shift predicted by Einstein, and (4) the strength of the general magnetic field.

Correlations between heights, intensities, and excitation potentials.—The flash spectrum is the only direct method of deriving heights in the chromosphere. The present discussion is confined to neutral *Fe* on account of the great number of lines involved, with wide ranges of wave-lengths, intensities, and excitation potentials. The strongest lines reach the greatest heights but are of least excitation potentials. Lines of Rowland intensity 6 and of excitation potential 0.07 volts extend to 1000 km, while lines of the same intensity but of higher excitation potential 4.75 volts reach only 400 km.

The Evershed effect found in sun-spots.—When the spectrum is divided at λ 4900 into two groups, and when averages are taken according to Rowland intensities, St. John has found that the motion in the line of sight for intensity n in the violet is equal to that for intensity $n+2$ in the red. When the flash-spectrum data are divided in similar manner and averages are taken, then both *heights* and *excitation potentials* show similar equalities for intensities 2 units greater in the red than in the violet. With use of Russell's methods of deriving the number of *effective atoms*, it is shown that the number of atoms involved in forming a line in the violet is the same as at 2 units of greater intensity in the red. For Rowland intensity 4 in the violet, two and a half times as many atoms are required to produce a spectral line as are necessary for a line of the same estimated intensity in the red. Hence, the underlying cause of the peculiarities noted are to be found in the *number of contributing atoms.*

The products of heights and excitation potentials is a constant, no matter what the Rowland intensity, when the material is divided at λ 4900 and averages are taken. Simple formulae are found for neutral *Fe* connecting average heights and average excitation potentials with Rowland intensities.

Wave-lengths in sun and vacuum arc.—Forty-eight multiplets of neutral *Fe* involving 309 lines are discussed. These were divided into multiplets consisting of strong, medium, and weak lines. From the differences sun *minus* vacuum arc was subtracted the predicted relativity shift. For the *Fe* spectrum as a whole this difference Δλ approximates zero. However, when the lines of the multiplets are divided into "main diagonal" and "side diagonals," then it is found that Δλ is greater on the main diagonal than on the side diagonals, and, moreover, Δλ is positive for multiplets of low excitation potential but negative for multiplets of high excitation potential.

The unit nature of multiplets is illustrated by $a^5F - y^5D^\circ$, showing close correlations between intensities, heights from flash spectrum, Evershed effect, and differences in the wave-length sun *minus* vacuum arc.

The differences in the number of atoms involved and the differences in concentration between multiplets of low and high excitation potentials give a ready means of explaining the differences in "effective heights" of strong and weak spectral lines.

Unsöld's theory must be interpreted so as to permit, in a single multiplet, not only differences in heights, but also differences in other related phenomena.

A circulation of Fe vapor in the chromosphere must be postulated, the atoms ascending through the medium of many weak lines of high excitation potential, the maximum velocity from the flash spectrum being −0.2 km per second. The atoms, on the other

hand, descend through the medium of relatively fewer lines of great strength but of low excitation potentials, the maximum velocity of *Fe* from flash spectrum being +0.4 km per second. A good agreement is found between the number of atoms ascending and those descending.

In the previous publication[1] entitled "The Spectrum of the Chromosphere" details were given for a total of 3250 lines measured on eclipse photographs. It was shown that information from the flash spectrum supplements that on the solar spectrum as contained in the *Revised Rowland* in two different directions: (1) the heights in kilometers attained by each line, and (2) the independent estimate of intensities on the Rowland scale of each of the emission lines of the chromospheric spectrum.

The present publication will be confined to neutral iron, and the discussion will be further restricted to problems involving heights or levels derived from the flash spectrum. In a future publication other elements (including ionized iron) will be treated and an attempt will be made to investigate conditions of temperatures, pressures, and distribution of atoms in the chromosphere.

The reasons for choosing neutral iron for the present publication are evident. Iron is very abundant in the sun and is represented by many spectral lines. In the *Revised Rowland* there are 3288 lines ascribed to neutral *Fe*. In the flash spectrum this element is the preponderant source of 1222 lines out of a total of 3250, or 37.6 per cent of the whole. The iron lines in the solar spectrum are found at all wave-lengths. By reference to Table I, *Astrophysical Journal*, **71**, 7, 1930, it will be seen that although the lines thin out at the red end (as is found for all elements) there is not the great concentration in the violet which takes place, for instance, with hydrogen or enhanced titanium.

Investigations involving iron have the additional advantage that more measures have been made in the laboratory on this element than on any other single one. The Mount Wilson observers have divided the lines of iron into different classes according to temperature and according to pressure. More recently, through the investigations of Russell and many others, the *Fe* lines have been grouped into multiplets for which have been derived values of the excitation potentials.

[1] *Astrophysical Journal*, **71**, 1, 1930.

At the Allegheny Observatory and the Bureau of Standards magnificent work has been carried out under the direction of K. Burns on the determinations of precise wave-lengths by interferometer methods of the iron arc in a vacuum. These wave-lengths, when reduced to the same system as the *Revised Rowland*, provide a powerful means of investigating the relativity shift in the sun as predicted by Einstein.

THE IMPORTANCE OF HEIGHTS IN THE INTERPRETATION OF SPECTRA

It has been almost universally agreed among astronomers that the heights or levels above the photosphere have a very important function in the interpretation of all solar phenomena, and this point of view has been extended to stellar investigations as well. At the Mount Wilson Observatory, mainly through the work of St. John,[1] a very strong structure has been built. It has been shown that in the sun a line of Rowland intensity 10 takes its origin at a higher level above the photosphere than a line of intensity 4, and this in turn is at a greater elevation than a line of intensity 0. It has been further found that the measures of the rotation of the sun determined by spectroscopic methods give conflicting information when lines of different elements or different intensities are employed. Many observatories in America and Europe have engaged in this project. At the time the plan was put into effect, a spectroscopic line seemed to be a very elementary affair. When high dispersion was used the wave-lengths seemed to have a high degree of precision. In fact, it looked like a very simple problem to place the slit of the spectrograph first on the eastern and then on the western limb of the sun, and then measure the differential Doppler effect. By changing the slit to different heliographic latitudes, it seemed to be of the utmost degree of simplicity to derive a very accurate law of solar rotation. But alas! The results for the solar rotation derived at each observatory differed from those at every other observatory. There seemed to be not only very large accidental but also large systematic differences in wave-length. The latter were very large in amount. Adams and Evershed independently found that the period

[1] *Mt. Wilson Contr.*, No. 348; *Astrophysical Journal*, **67**, 195, 1928.

of rotation for the $H\alpha$ line of hydrogen is 24 days, while for the vapors lying close to the photosphere the rotation period is 25.35 days. This difference must mean that there is a high east wind in the upper solar atmosphere of approximately 400 km per hour. To interpret the conflicting results it has been necessary to assume that the Fraunhofer lines take their origins at definite restricted levels[1] in the chromosphere.

In investigations of the spectra of spots on the sun, Evershed found displacements in wave-length that have been interpreted as due to the motions of vapors in the solar vortex. St. John, of Mount Wilson, has abundantly verified Evershed's work[2] and has interpreted the effects on the basis of heights above the sun. At 1500 km above the solar surface there is a level of inversion. Above this level gases flow into the spot, while below this level the flow is out of the spot, the whole making a gigantic vortex. According to St. John,[3] "In the observation of these velocities we have a method of sounding the solar atmosphere and of allocating the relative levels of the lines."

In the discussion of the relativity shift in the sun, St. John interprets the results by assuming that the stronger lines reach greater heights than the weaker lines, and he finds that for Rowland intensity 6 the Einstein theory gives the shift actually found in the sun. More intense lines show a greater shift to the red, while fainter lines show a less shift.

In addition, levels in the sun are intimately connected with the strength of the general magnetic field. Hence in the sun there are four independent lines of investigation which tell a consistent story about the importance of heights or levels above the photosphere. These are (1) solar rotation, (2) Evershed effect in sun-spots, (3) relativity shift, and (4) strength of the general magnetic field. The solar heights almost universally used in these investigations have been found in the *Publications of the Leander McCormick Observatory*, Volume II, *Part 2*, or *Astrophysical Journal*, **38**, 407, 1913. In finding correlations by means of these four independent lines of investigation with heights above the photosphere, the only method

[1] Cf. *Eclipses of the Sun* (2d ed.), p. 253.

[2] *Mt. Wilson Contr.*, No. 88; *Astrophysical Journal*, **40**, 356, 1914.

[3] *Loc. cit.*

heretofore possible has been to take averages of the heights attained by the lines of any element in the sun (like neutral *Fe*), all lines of equal solar intensity being assumed to have the same height.

In recent years, by the combination of lines into multiplets with the determination of excitation potentials, the problem has been completely changed. It is found for neutral *Fe* (and also for all elements, both neutral and ionized) that the strongest lines always belong to the multiplets of low excitation potential. The height in the chromosphere reached by a line of intensity 6 has no longer any definite meaning unless the value of the excitation potential is known. For example, it will be seen from Table II that four *Fe* lines of intensity 6 in the sun of the lowest excitation potential 0.07 volts extend to 1075 km, while four lines of the same intensity, but of high excitation potential averaging 4.75 volts, extend only to a height of 400 km above the photosphere. In view of these facts it is necessary to rediscuss the connection between levels in the photosphere and the other related phenomena, taking account of the variation in excitation potentials for lines of the same intensity in the sun. The heights or levels to be used for this purpose are found in the recent publication in *Astrophysical Journal*, **71**, 1, 1930.

HEIGHTS DERIVED FROM THE FLASH SPECTRUM

In the previous publication the method is described[1] for deriving levels in the chromosphere. The heights published are primarily those of the eclipse of 1905 from photographs obtained at the end of totality. They refer to a quiescent condition of the sun. In view of the fact that these heights are of fundamental importance in discussing related solar phenomena, it will be well to examine carefully into the significance and reliability of these heights. To simplify the description in what follows we shall refer to the flash spectrum at the end of totality. With proper changes in phraseology reference could be made to the first flash at the beginning of totality.

In view of the uncertainty still attaching to the times of beginning and ending of totality, it is ordinarily necessary at an eclipse to begin the exposure for the second flash five to seven seconds before the expected end of totality. By following this practice the usual

[1] *Op. cit.*, p. 99.

result is that the high-level lines have a longer exposure than the low-lying vapors, with the necessary consequence that the high-level lines have a relatively greater intensity and the low-level lines a less intensity than if a constant exposure had been given to all lines. As a further consequence, the heights measured for the fainter and low-lying lines of an element, like neutral *Fe*, are smaller, while for the stronger lines the heights are greater than if a uniform exposure had been given.

At the eclipse of 1905 the exposure for the second flash was timed so as to begin 7.4 seconds before the calculated end of totality. By reference[1] to *Eclipses of the Sun*, page 67, it will be seen that the duration of totality was actually six seconds less than the calculated value, and hence the total duration of the exposure for the second flash was only one and four-tenths seconds. If the exposure for the flash had been planned to begin five seconds before the calculated end of totality, the flash spectrum would have been missed entirely! With the short duration of exposure actually given to the flash in 1905, there can be little difference in the relative exposures between high- and low-level lines; in fact, any systematic differences of this sort must be less than the accidental errors of observation. In addition to the "happy accidents" that conspired together for the writer at the eclipse of 1905,[2] another must now be added, namely, a duration of totality much less than was expected.

The heights of the low-lying lines were estimated in steps of 50 km, medium level in steps of 100 km, and highest level in steps of 200 km. On account of the excellent definition of the 1905 spectra which gave a well-defined crescent for each spectral line, the writer feels confident that the accidental error in measuring each line is about 10 per cent of the height attained by the spectral line. As already stated, it is felt that the systematic errors in the heights between the weak, low-lying lines and the strong ones of high level are small enough to be negligible.

In view of the many different interpretations placed by astronomers on the heights derived from the flash spectrum, it is necessary again to call attention[3] to the real meaning of these heights. These

[1] Cf. also *Lick Observatory Bulletin*, **4**, 118, 1905.

[2] *Op. cit.*, p. 5.

[3] *Ibid.*, p. 49.

depend on the lengths of the crescent arcs. The tips of these arcs fade off gradually. At a certain definite intensity, depending on the threshold value of the plate at the particular region of the spectrum investigated, the arcs can no longer be seen on the original photograph, and this point on the arc is measured in order to derive the heights. In the flash spectrum the atoms are emitting radiation. The intensity of a spectral line depends primarily on the number of emitting atoms. For an element like neutral iron it must be assumed that the chromospheric vapors are densest and the atoms most numerous at low-lying levels near the photosphere, with the atoms thinning out gradually at higher elevations. When the atoms reach a certain definite concentration, or when there are a certain number of atoms per unit volume, or per centimeter, then the radiation is sufficiently intense to record itself on the photograph.

The lengths of the crescent arcs, and consequently the heights in the chromosphere, depend on the number of emitting atoms involved. Manifestly, the heights derived from the flash spectrum cannot, and do not, mean the maximum heights to which atoms are shot as the result of solar activity, but rather until the atoms reach a certain definite concentration, C. If the photographic film employed for the flash spectrum were equally sensitive in all spectral regions, then C would be a constant; but if the sensitivity of the plate is less in one region than in another, a higher concentration of atoms is necessary before a spectral line is recorded or reaches the threshold value on the plate.

If a line belongs to a multiplet of known excitation potential, modern atomic theory gives the relative number of atoms involved, and a calibration is possible of the scale of intensities and heights at different spectral regions. This has been done for the flash spectrum.

It will be shown later in this publication (p. 163) that the maximum sensitivity of the spectrograph (including silver-on-glass mirror of the coelostat and concave grating) and the photographic plate was in the spectral region from λ 3700 to λ 4500. The average heights in this region which are given in Table V of the previous publication[1] are greater than in the balance of the spectrum. To the

[1] *Ibid.*, p. 11.

violet of λ 3400 the sensitivity falls off rapidly and the heights are known with less accuracy than for the balance of the spectrum. For any discussion involving heights, this ultra-violet region should be given less weight. It has been found that the scale of heights recorded in Table V in the most sensitive region λ 3700 to λ 4500 is on the whole about 10 per cent greater than in the regions from λ 3400 to λ 3700 and from λ 4500 to λ 6000. As most of the well-known strong lines like H and K, many of the hydrogen series, and the enhanced lines of various elements like titanium and strontium belong in this region, it should be adopted as standard. From λ 6000 to the extreme red the heights published depend on the 1925 eclipse. To reduce all heights derived from the flash spectrum to one standard, it would appear to be necessary to increase by 10 per cent the published heights in the region to the violet of λ 3700 and from λ 4500 to λ 6000. This 10 per cent increase is about equal to the value of the accidental error of the determination of the height of each line. (This will be discussed later.)

It is but natural to think that the crescent arcs fade off gradually and that therefore it must be difficult to estimate when the tips of the crescents have a certain definite blackening on the original photograph which was taken to be, and was measured as, the end of the tip. Attention must be called again to the exquisite definition of the 1905 flash spectra, dependent on good focus but more especially on good seeing, and also to the fact that the writer attempted to employ a definite and constant blackening on the original photograph as his estimate of the end of the crescent line. As already stated, this blackening requires a certain number of emitting atoms. An immediate result will follow: In a region of the flash spectrum where the sensitivity of the photograph is constant, a ready means is found for finding the concentration of atoms for any element at different heights above the photosphere, or, in other words, to find the density distribution of gases in the chromosphere. (This will be treated in detail in the subsequent publication.) Variations in the sensitivity of the photograph can be allowed for in the manner already alluded to, or by following the methods of Russell, Adams, and Miss Moore[1] in the calibration of Rowland's scale.

[1] *Mt. Wilson Contr.*, No. 358; *Astrophysical Journal*, **68**, 1, 1928.

The writer had additional aids in keeping the scale of heights constant at different spectral regions. In Plate II of the earlier publication is shown the interruption of the crescent arcs by irregularities on the edge of the moon. By reference to charts of the moon, such, for instance, as *Selenographische Koordinaten* by Frederick Hayn,[1] it will be found from his Plates III and X that one reason for the total eclipse ending earlier than was expected was that the sun's light shone through a depression on the edge of the moon, the center of this depression from Plate X being at position angle 268°. This irregularity is the explanation of the peculiarities in the flash photograph described in the earlier publication at page 50. As the irregularities on the moon's edge which cause effects in the heights measured from spectral lines are merely relative in character, it will be seen that a higher level on the moon called a "plateau"[2] caused the interruption of the crescent arcs referred to. Hence as a consequence, if a line of the flash spectrum showed itself on the photograph above this plateau, its height was estimated to be 600 km or more, while on the other hand, if it did not show, the level was estimated to be 500 km or less. This so-called plateau gave the means of keeping the scale of heights fairly constant throughout the whole extent of the spectrum. It in nowise interfered with the estimation of small heights.

At the 1905 eclipse a photograph was taken which ended three seconds before the reappearance of the sun's limb. On this photograph the low-lying vapors of the chromosphere were still covered, with the result that an excellent observational means was afforded of calibrating the heights of medium level. In particular it helped the writer to decide when a spectral line extended 1000 km or more above the photosphere.

With all these aids in mind, it is felt that confidence may be had in the accuracy of the heights in the chromosphere derived from the flash spectrum.

SCALES OF INTENSITIES

In the discussion of neutral *Fe*, there are three different scales of intensities that must be considered, all of them being arbitrary

[1] *Abhandlungen der mathematischen u. physikalischen Klasse der Königlichen Sächische Gesellschaft der Wissenschaften*, **33**, 1, 1914.

[2] *Op. cit.*, p. 50.

scales. They are as follows: (1) the Rowland scale of the solar spectrum; (2) the independent estimates from the flash spectrum, which were made to fit the Rowland scale; and (3) A. S. King's scale from laboratory investigations. According to Russell,[1] King's scale, which was intended to represent the actual intensities of the lines, is a remarkably homogeneous scale. Russell further finds that King's estimated intensities are very nearly proportional to the square roots of the relative numbers of atoms predicted by the theory of multiplets. "The agreement is so close that these estimates, especially when averages for several multiplets are available, are clearly almost as valuable as actual measures, when once the significance of the empirical scale has been found."

King's scale is closely related to that of Rowland and to that of the flash spectrum. Russell's tables of intensities of lines in multiplets[2] have been extensively used in the present discussion. The comparisons of the three scales of intensities alluded to and the theoretical intensities have revealed certain errors in the Rowland estimates.

IMPORTANCE OF EXCITATION POTENTIALS

A person having no knowledge of the theory underlying multiplet groups would not go very far in the practical operation of correlating intensities and heights in the chromosphere before the fact would be forced upon his attention that the lines of greatest intensity and of greatest heights belong to the multiplets of lowest excitation potential. Neutral *Fe* is especially valuable for such an investigation on account of the wide range of excitation potentials. In the discussion which follows the intensity scale is that of the *Revised Rowland*.

In the comparison of heights in the chromosphere with Rowland intensities and also in the discussion of the correlations of both with excitation potentials, it will be best to take up first in detail the multiplets of lowest excitation potentials. In the description of these matters it is rather unfortunate that the word "level" is used in two entirely different meanings. We speak of levels in the chromosphere, or differences in heights measured in kilometers. We likewise speak of atomic levels with differences measured in volts. In order to prevent ambiguity, the word "level" will be used in the

[1] *Proceedings of the National Academy of Sciences*, 11, 322, 1925. [2] *Ibid.*

following to refer to spectroscopic terms and the word "heights" to refer to the chromosphere.

The lowest level found in the chromospheric spectrum of neutral *Fe* is the a^5D-level with average excitation potential of 0.07 volts; the next lowest level is a^5F, of average excitation potential 0.92 volts. There are three multiplets with a^5D as the lower term[1] with lines of great intensity and with wave-lengths greater than λ 3400. They are $a^5D-z^5P^o$ lying between the wave-lengths 3440 and 3526, $a^5D-z^5F^o$ (3649–3748), and $a^5D-z^5D^o$ (3824–3930). The three multiplets with a^5F as the lower term are $a^5F-z^5G^o$ (3540–3647), $a^5F-y^5F^o$ (3687–3799), and $a^5F-y^5D^o$ (3820–3940). It is interesting to note that the multiplets of excitation potential 0.07 volts in each of the three cases have approximately the same wave-lengths as those of the higher excitation potential. The result will be that when taking averages of Rowland's intensities or heights from the flash spectrum the averages will be entirely independent of differences in the sensitivity of the photographs at different spectral regions.

In Table I the heights from the flash spectrum as printed in the previous publication are given for the individual lines arranged according to their Rowland intensities. In order to simplify the printing, certain Rowland intensities are grouped together.

In addition to the three multiplets of excitation potential involving a^5D as the lower term, there are three other multiplets, intersystem combinations with septets as the higher terms. For the multiplets with excitation potential 0.92 and lower term a^5F, there is a total altogether of twelve multiplets, the higher terms of the multiplets being quintets, triplets, or septets. In Table I, in the lines giving "Means," the upper number in each case gives the average height in kilometers, the lower the number of lines involved. It is again fortunate that all of the multiplets for each of the two excitation potentials considered (0.07 and 0.92) lie on the average in the same spectral regions.

The heights given from Table I and generally in all that follows refer to lines in the flash spectrum where *Fe* is the predominant source; in other words, the heights refer to pure *Fe* lines and blended

[1] The notation adopted for multiplets throughout is that of Russell, Shenstone, and Turner, *Physical Review*, **33**, 900, 1929.

lines taken together. Comparisons of heights and intensities for pure *Fe* lines and for blended lines considered separately give the same average results (as shown in Table IV), the increase in the

TABLE I

ROWLAND INTENSITIES AND HEIGHTS FROM FLASH SPECTRUM

Multiplet and Spectral Region	20–40	12–15	9–10	8	7	6	5	4	3	2	1
	Excitation Potential = 0.07 Volts										
$a^5D-z^5P^o$ (3440–3526)	1500	1500	800 800	800 800 800	....	1000	....	....	....	....	....
$a^5D-z^5F^o$ (3649–3748)	2000 2000	2000	600 1200	....	800	1000	600	500	....	....	....
$a^5D-z^5D^o$ (3824–3930)	2500	1500 1500	800 1200	1500 1200 1500 1500	1200	1500	....	....	....	....	....
Mean of the three multiplets above	2000 4	1625 4	900 6	1186 7	1000 2	1167 3	600 1	500 1	....	....	....
Mean of all multiplets..........	2000 4	1625 4	900 6	1186 7	1000 2	1075 4	600 5	517 3	428 7	444 8	350 3
	Excitation Potential = 0.92 Volts										
$a^5F-z^5G^o$ (3540–3647)	1500 1200 1200	1200 1200 1500	......	500	......	......	......	400	600	......	......
$a^5F-y^5F^o$ (3687–3799)	1000	1000	1000 750	800 1000 800	750	600 1000	....	....	....	....	....
$a^5F-y^5D^o$ (3820–3940)	1500 1500	....	750 1000	1200 1500	1000 800	1000	800 600 600	....	....	....	....
Mean of the three multiplets above	1317 6	1225 4	875 4	967 6	850 3	867 3	667 3	400 1	600 1	....	....
Mean of all multiplets..........	1300 7	1225 4	875 4	833 9	692 6	638 8	628 11	504 12	442 13	400 1	333 3

Rowland intensity coming from the blend of two (or more) lines corresponding to the increase in height. As the numbers of pure and of blended lines for *Fe* amount to hundreds in each case, it was decided generally to take advantage of the greater number of lines when forming averages.

In Table II similar information is given for all of the lines found

in multiplets of neutral *Fe*, and arranged in order of increasing excitation potentials, the total number of lines involved being 789. The following facts should be noted: (1) The strongest lines of neutral *Fe* in the sun, Rowland intensity 40, belong to multiplets of the lowest excitation potential 0.07 volts. (2) With increase of excitation potential the maximum intensity of a line in a multiplet steadily decreases. (3) For multiplets of the same average excitation

TABLE II*

EXCITATION POTENTIALS, ROWLAND INTENSITIES AND HEIGHTS

Excitation Potential	20–40	12–15	10	7–9	6	5	4	3	2	1	0
0.07	2000 4	1625 4	900 4	1100 11	1075 4	600 5	517 3	428 7	444 8	350 3	....
0.92	1300 7	1225 4	917 3	767 15	638 8	628 11	504 12	442 13	400 1	333 3	....
1.52	1650 2	1525 4	1075 4	875 6	600 2	500 3	435 13	417 9	383 3	....	....
2.18–2.49	.....	.....	775 4	638 16	565 24	524 17	467 17	419 27	403 16	318 8	....
2.50–2.99	.....	.....	500 1	567 15	537 17	493 31	479 38	433 38	412 24	329 12	300 2
3.00–3.49	.....	.....	.....	542 6	450 9	447 18	440 21	425 26	364 21	325 6	300 1
3.50–3.99	.....	.....	.....	520 5	400 4	421 7	373 15	387 15	375 14	350 5	300 2
4.00–4.49	.....	.....	.....	400 1	400 2	415 10	390 10	372 23	339 32	321 17	250 7
4.50–4.99	.....	.....	.....	.....	400 4	383 6	400 6	394 9	333 3	300 2	....

* The upper quantity gives the height in kilometers; the lower gives the number of spectral lines involved.

potential there is a close correlation between intensities and heights. The heights diminish to the right in Table II for each of the excitation potentials considered. (4) For any given Rowland intensity, such as 6, the heights diminish (vertically in the column) as the excitation potentials are increased. To know the height corresponding to a line of intensity 6 the value of the excitation potential is necessary.

Smoothed values of the heights in Table II for certain average values of excitation potential are given in Figure 1.

CALIBRATION OF HEIGHTS FROM FLASH SPECTRUM

To find whether the heights in one region of the spectrum are systematically greater than in another it would seem to be an easy matter to compare the heights corresponding to different intensities in the different regions under consideration. The question, however, cannot be solved so simply since excitation potentials are also involved.

The spectral lines of low excitation potentials are concentrated toward the violet end of the spectrum while on the contrary the lines of high excitation potentials are on the average at much greater

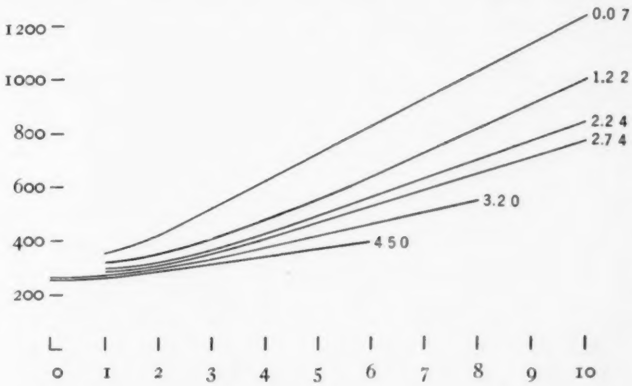


FIG. 1.—Heights, Rowland intensities, and excitation potentials

wave-lengths. Fortunately, however, for lines of medium excitation potential, from 2.18 to 2.99 volts, there are a total of 308 lines with sufficient range in wave-length to permit comparisons. In Table III the lines are divided in wave-length at λ 4500. They are also grouped together according to excitation potential, those of lower value (2.18–2.49 volts) and those with higher value. By comparing the average heights for the same intensity to the violet and red of λ 4500, we find in each case that the violet heights are greater than those to the red. However, if the heights, particularly of the stronger lines, are compared for the lower values of excitation potential (2.18–2.49 volts) with the higher values (2.50–2.99 volts), it is found that greater heights are shown by the lines of the smaller values of excitation potential, both in the violet and in the red. This is quite

in keeping with the general conclusion that the greater heights are always associated with low values of excitation potential.

The problem of heights and intensities is so closely bound up with excitation potentials that it is difficult to come to positive conclusions. However, taking the information from the lines in Table III, supplemented by similar information from other elements than *Fe*, both neutral and enhanced, it seems quite possible to conclude

TABLE III

Excitation Potential	Spectral Region	10	7–9	6	5	4	3	2	1	0
2.18 to 2.49	3400 to 4500	950 2	729 7	617 15	538 13	486 11	468 14	450 8	325 2	....
	4500 to 7065	600 2	567 9	478 9	475 4	433 6	366 13	356 8	315 6	....
2.50 to 2.99	3400 to 4500		590 10	577 12	509 22	493 27	484 22	461 13	367 3	....
	4500 to 7065	500 1	520 5	440 5	455 9	445 11	362 16	354 11	317 9	300 2
2.18 to 2.99	3400 to 4500	950 2	647 17	594 27	520 35	491 38	478 36	457 21	350 5	....
	4500 to 7065	567 3	550 14	464 14	461 13	441 17	364 29	355 19	316 15	300 2

that in the most sensitive part of the photographs of the flash spectrum of 1905 from λ 3700 to λ 4500 the heights may be systematically about 10 per cent greater than in the balance of the region investigated at this eclipse.

HEIGHTS FROM THE EVERSHED EFFECT IN SUN-SPOTS

In Table II the heights and intensities are given for all neutral *Fe* lines for which excitation potentials are known. In Table IV, on the contrary, the heights and intensities are given for *all* of the *Fe* lines in the flash spectrum except a few blended lines. The tabular material is divided into three parts. In the upper part are those

TABLE IV

Rowland Intensities, Heights, and Excitation Potentials

Region		0	1	2	3	4	5	6	7	8	9	10	12	15–18	20–40
Pure *Fe* lines: Unblended	3286–4900...	316 6 3.20 2	376 23 3.09 12	397 53 3.11 26	440 63 2.82 34	440 55 2.59 41	507 43 2.42 36	644 27 2.19 22	715 13 1.66 13	877 15 1.15 15	788 4 0.97 4	967 9 0.88 9	1500 2 0.48 2	1400 7 1.42 7	1627 11 0.78 11
	4900–7023...	284 37 3.99 10	304 62 3.20 23	337 68 3.59 45	366 69 3.13 55	450 45 3.35 41	420 40 3.12 37	456 27 2.89 23	514 14 2.80 14	560 5 2.11 5	600 1 2.42 1	500 1 2.82 1	....	....	....
	3286–7023...	289 43 3.85 12	323 85 3.16 35	363 121 3.41 71	401 132 3.01 89	422 100 2.97 82	465 83 2.81 73	550 54 2.55 45	611 27 2.25 27	805 20 1.39 20	750 5 1.26 5	920 10 1.18 10	1500 2 0.48 2	1400 7 1.42 7	1627 11 0.78 11
Blended lines	3286–4900...	350 5 1.27 2	369 24 2.79 10	406 36 2.87 19	485 59 2.58 37	492 69 2.65 45	497 63 2.67 47	525 44 2.35 35	562 36 2.47 31	607 22 2.50 15	653 15 2.25 14	915 10 1.61 10	760 5 2.01 4	1287 6 0.83 6	1467 3 0.64 3
	4900–7023...	300 8 2.20 2	325 16 4.20 7	328 18 4.00 7	338 12 3.13 10	428 9 3.72 7	413 8 2.93 7	460 10 2.85 10	514 7 2.34 7	510 5 1.54 5	....	700 2 3.00 2	....	....	....
	3286–7023...	319 13 1.74 4	351 40 3.38 17	380 54 2.79 26	460 71 2.48 47	484 78 2.79 52	488 71 2.70 54	513 54 2.46 45	555 43 2.44 38	589 27 2.26 20	653 15 2.25 14	780 12 1.84 12	760 5 2.01 4	1287 6 0.83 6	1467 3 0.64 3
All lines	3286–4900...	331 11 2.26 4	372 47 2.95 22	390 89 3.01 45	462 122 2.70 71	469 124 2.62 86	501 106 2.54 83	570 71 2.29 57	603 49 2.23 44	720 37 1.82 30	681 19 1.96 18	940 19 1.27 19	971 7 1.50 6	1325 13 1.00 13	1593 14 0.75 14
	4900–7023...	287 45 3.69 12	308 78 3.44 30	330 86 3.64 52	362 81 3.13 65	405 54 3.41 48	405 48 3.16 44	456 37 2.57 33	514 21 2.65 21	535 10 1.82 10	600 1 2.42 1	633 3 2.94 3	....	....	....
	3286–7023...	296 56 3.33 16	332 125 3.23 52	361 175 3.35 97	422 203 2.90 136	450 178 2.90 134	446 154 2.77 127	532 108 2.39 90	576 70 2.36 65	681 47 1.82 40	947 20 1.98 19	898 22 1.49 22	971 7 1.50 6	1325 12 1.00 13	1593 14 0.75 14
Evershed effect at λ 5000....		.030 2.0	.028 1.7	0.25 1.5	0.23 1.4	.021 1.2	.019 1.1	.016 1.0	.013 0.8	.010 0.6	.005 0.3	.003 0.2	.002 0.1	.001 0.1	.000 0.0

lines which are single *Fe* lines (without blends) both in flash spectrum and in the *Revised Rowland*. Then follow the lines which are blended but with *Fe* as the predominant element. The pure *Fe* lines and those blended are then averaged together. Each section of the table is divided in wave-lengths at λ 4900. At the bottom of the table is given the radial motion observed in the penumbra of sunspots, the Evershed effect, measured by St. John at Mount Wilson Observatory, the first line giving the value in angstroms and the second in kilometers per second.

The intensities are Rowland's. The first line in each of the three sections of the table gives the average height in kilometers, immediately followed by the number of spectral lines on which this average depends. The second line in each case gives the average excitation potential and the number of lines. The following conclusions are drawn from Table IV:

1. For the pure iron lines (at the top of the table), the excitation potentials are known for all lines of intensity 7 or greater. For the fainter lines, the percentage of lines with known excitation potentials becomes less and less for fainter and still fainter *Fe* lines. This is what one would naturally expect.

2. The strongest lines, those which reach heights in excess of 700 km, are all without exception to the violet of λ 4900, and all have small excitation potentials, less than 2.00 volts.

3. In passing from weak to strong lines, that is, to the right in the table, there is in all sections a steady increase in heights and an equally uniform decrease in the value of the excitation potential.

4. The heights on the whole average about the same for the pure *Fe* lines as for those blended. Consequently, any conclusions based on all lines, pure and blended combined, should represent *Fe* in a satisfactory manner. The advantage of the greater number of lines in averaging out accidental errors is obvious.

5. For any given intensity the heights are greater to the violet of λ 4900 than to the red.

6. On the contrary, the average excitation potential for any intensity is less in the violet than in the red.

7. An increase in height for any Rowland intensity such as 6 therefore corresponds to a decrease in excitation potential. This is given in another form in Table II and graphically in Figure 1.

8. To get the same average height in the red as to the violet of λ 4900, it is necessary to add 2 units of intensity to the right in Table IV, or 2 units of greater strength in the red. This is shown in all three sections of the table, but is best seen in the combination of "All Lines" on account of their larger number.

9. In quite a similar way, to reach the same excitation potential in the red as in the violet, it is necessary to go to lines of 2 Rowland units of greater intensity in red than in violet.

10. The Evershed effect in sun-spots has been discussed by St. John in a number of *Communications* from the Mount Wilson Observatory (Nos. 69, 74, 88, 348, and 390). The average value found is given at the bottom of Table IV, showing a decrease in the motions in sun-spots with increase of strength and height of *Fe* lines. St. John has interpreted the Evershed effect as due to heights above the photosphere.

11. St. John further finds[1] that to get the same measured value of the Evershed effect in the red as in the violet it is necessary to go 2 units of greater intensity in the red. Compare this conclusion with (8) and (9) above.

The motions in the line of sight of the gases in the penumbral regions of sun-spots can be measured with a large degree of precision on account of the high dispersion employed at Mount Wilson. When the measures of the Evershed effect from the individual *Fe* lines[2] are combined into averages, and the spectral lines are then arranged in various manners according to Rowland intensities, heights from the flash spectrum, excitation potentials, and spectral regions, conclusive evidence is found that the size of the Evershed effect does depend primarily on the heights, which is in exact agreement with the interpretation of St. John. On the assumption, now thoroughly well founded, that a spot is a vortex on the sun, it appears abundantly verified that the indirect determination of relative heights from the Evershed effect tell a very consistent story with the direct measurement of heights from the flash spectrum.

In Table IV the heights and excitation potentials of neutral *Fe* lines in the chromosphere are separated into two groups at λ 4900. The number of lines of *Fe* diminish as the ends of the spectrum are

[1] *Mt. Wilson Contr.*, No. 69; *Astrophysical Journal*, **37**, 322, 1913. [2] *Ibid.*

approached, and the mean wave-length of the lines in the violet section of the table is about λ 4200 and at the red about λ 5800. By combining the calibration of the Rowland scale at various wave-lengths[1] with Unsöld's measures[2] of line contours from which was derived the total numbers of atoms contributing to certain Fraunhofer lines in various parts of the spectrum, H. N. Russell[3] has calculated the number of atoms (N) effective in producing a line of given intensity in any spectral region. Thus, he finds values of log N given in Table V.

The calibration is admittedly very rough, the number of effective atoms for Rowland intensity 0 at λ 4200 being assumed equal in number to those at λ 5800.

TABLE V

Intensity	0	1	2	3	4	5	6	7	8
Log N at λ 4200	0.0	0.58	1.14	1.69	2.22	2.65	2.97	3.18	3.33
Log N at λ 5800	.0	.47	0.94	1.38	1.82	2.17	2.44	2.61	2.73
Log $N \frac{\lambda\ 4200}{\lambda\ 5800}$	0.0	0.11	0.20	0.31	0.40	0.48	0.53	0.57	0.60
N (4200):N (5800)	1.0	1.3	1.6	2.0	2.5	3.0	3.4	3.7	4.0

From this entirely independent material, however, we see the same tendency for a line of Rowland intensity n in the violet to be equivalent to a line of Rowland intensity $n+2$ in the red. Thus, a spectral line produced by a given number of atoms has the same Evershed effect, the same height in the flash spectrum, and the same average excitation potential throughout the spectrum. However, in any given region of the spectrum the height of a line of given intensity (produced by a given number of atoms) depends upon the excitation potential, as shown above.

The relative numbers of atoms given in Table V in no way depends on the discussion of the flash spectrum. Russell has derived the values of N by taking the averages from numbers of lines of the same Rowland estimates of intensity. By using the material from the flash spectrum as given in Table IV, an independent check

[1] *Mt. Wilson Contr.*, No. 358; *Astrophysical Journal*, **68**, 1, 1928.

[2] *Zeitschrift für Physik*, **46**, 765, 1928.

[3] *Mt. Wilson Contr.*, No. 383; *Astrophysical Journal*, **70**, 11, 1929.

on the relative numbers of atoms involved may be derived by utilizing the average values of excitation potentials. Within errors of observation the results should agree. By following Russell's procedure the values of log *M* could have been calculated for the different multiplets entering into Table IV, but more simply, however, a smooth curve was drawn connecting excitation potential *E* and "Log *M* Computed." By using the excitation potentials from Table IV for Rowland intensities 0–8 inclusive, the values of log *M* were found. On account of the greater purity of the material, the "Unblended lines" were utilized for the purpose. Below are given the relative numbers of atoms found by this method in the violet at λ 4200 with respect to the number at λ 5800 and for equal values of Rowland intensities.

Intensity	0	1	2	3	4	5	6	7	8
$\frac{M \text{ at } \lambda\, 4200}{M \text{ at } \lambda\, 5800}$	2.0	1.3	2.0	1.6	2.5	1.6	2.5	5.0	5.0
$\frac{\text{Mean at } \lambda\, 4200}{\text{Mean at } \lambda\, 5800}$	1.5	1.3	1.8	1.8	2.5	2.3	3.0	4.4	4.5

The mean of the values of *M* and *N*, as given above, shows a steady increase in size with increasing Rowland intensity. If means are taken for *M* and *N* separately, weighted according to the number of lines in Table IV of each Rowland intensity, then the weighted mean of *M* is 2.2, and that of *N* is 2.3, a very close agreement. The mean of these two values, 2.25, corresponds to a line of Rowland intensity 3.8. For Rowland intensity 4, the mean vlaue of *M* and *N* is 2.5.

Hence, from this calibration we reach the conclusion that in the violet at λ 4200 there are required two and a half times as many atoms to give a line estimated by Rowland of intensity 4 as are required for a line estimated of the same intensity but in the yellow at λ 5800.

It has already been shown in the present discussion that on account of the greater sensitivity of the photograph of the flash spectrum in the region λλ 3700–4500, the heights within this portion may possibly be 10 per cent greater than in the balance of the spec-

trum. As a matter of fact, the heights in Table IV (with the exception of those corresponding to the greatest intensities) average about 10 per cent greater in the violet than in the red. Evidently either explanation (variation of the number of atoms required to produce a line of given Rowland intensity, or variation of the sensitivity of the flash film), or a combination of the two, may be used to explain the variation of the heights in the flash with wave-length. However, only the first will explain the variation in the Evershed effect and in the average excitation potential for a line of given intensity in different parts of the spectrum.

Therefore, so long as spectral observations on the sun are grouped together into various intensities, on Rowland's or any other scale, the average can represent only a first approximation to the truth. Further progress demands a knowledge of multiplet groups and excitation potentials from which may be derived the relative numbers of atoms involved. The present discussion, dealing only with neutral *Fe*, shows the great differences that are met when dealing with various spectral lines of the same Rowland intensity. The dependence on excitation potentials of both intensities and heights is shown in Table VI for other neutral elements than *Fe*. (Similar effects are found for the enhanced elements, but these will be discussed in the later publication.) In the table the elements are arranged alphabetically. The following conditions were imposed in the selection of the individual lines included in the table: (1) Within each element there was a wide range in excitation potentials; (2) the strongest lines only were listed, the basis of choice being King's well-known laboratory intensities; (3) in wave-lengths both the violet and red ends were avoided; (4) no intersystem combinations were included, except in the case of *Mg;* (5) lines blended in the smaller dispersion of the flash spectrum were avoided—in a few cases unimportant blends were included; (6) the selection within the multiplet was confined to the three strongest lines (when there were more than this number).

The intensities in the flash spectrum agree on the average with those of the *Revised Rowland*. From the material of the table, for each of the elements considered, in comparing lines of low excitation potential with those of high excitation potential, the following facts

TABLE VI

INTENSITIES AND HEIGHTS FOR NEUTRAL ELEMENTS

Element	Excitation Potential	Multiplet	Wave-Length	Intensities: King	Intensities: Disk	Intensities: Flash	Intensities: Spot	Inner-Quantum Numbers	Height in Km
Al.....	0.00	$a^2P^o-z^2S$	3944.03	(10 R)	15	25	10	$\frac{1}{2}-\frac{1}{2}$	2000
			3961.54	(10 R)	20	35	15	$1\frac{1}{2}-\frac{1}{2}$	2000
Al.....	3.13	$z^2S-f^2P^o$	6696.06	(3)	1	......	2	$\frac{1}{2}-1\frac{1}{2}$	......
			6698.73	(3)	0	......	0	$\frac{1}{2}-\frac{1}{2}$	......
Ca.....	0.00	$4^1S-4^1P^o$	4226.73	500 R I	20d	40	40	0 −1	5000
Ca.....	1.88	$4^3P^o-5^3S$	6102.72	80 II	9	8	25	0 −1	800
			6122.22	100 II	10	10	28	1 −1	800
			6162.18	150 II	15	15	35	2 −1	1000
Ca.....	2.51	3^3D-dp^3F	6439.09	150 II	8	9	12	3 −4	600
			6471.66	40 II	5	3	10	3 −3	400
			6493.79	80 II	6	4	12	1 −2	400
Ca.....	2.92	$4^1P^o-6^1S$	5512.98	20 n III	4	2	8	1 −0	350
Cr.....	0.00	$a^7S-z^7P^o$	4254.34	500 R II	8	25	12	3 −4	1500
			4274.79	400 R II	7d?	20	12	3 −3	1500
			4289.73	350 R II	5	18	8	3 −2	1500
Cr.....	0.94	$a^5S-z^5P^o$	5204.53	150 r II	5	7d	12^2	2 −1	500
			5206.05	200 r II	5	8	8	2 −2	600
			5208.44	300 r II	5	12	9	2 −3	600
Cr.....	3.13	$z^7F^o-g^7D$	4689.40	8 III	2	2	3	3 −2	350
			4708.05	15 III	2	1	4	5 −4	450
			4718.45	20 III	3	3	4	6 −5	400
Mg.....	0.00	$3^1S-3^3P^o$	4571.11	5 I A	5	6	8	0 −1	700
Mg.....	2.70	$3^3P^o-3^3D$	3829.36	40 II	10	40	......	0	6000
			3832.30	80 r II	15	50	......	1	6000
			3838.28	100 r II	25	60	......	2	7000
Mg.....	2.70	$3^3P^o-4^3S$	5167.30	40 II	15	18	16	0 −1	1500
			5172.67	80 II	20	30	22	1 −1	2000
			5183.60	125 II	30	40	30	2 −1	2500
Mg.....	4.33	$3^1P^o-5^1D$	4703.07	40 V	10	6	9	1 −2	500
Mn.....	0.00	$a^6S-z^6P^o$	4030.76	200 R I	9^2	20	12	$2\frac{1}{2}-3\frac{1}{2}$	1000
			4033.07	150 R I	7d?	18	9	$2\frac{1}{2}-2\frac{1}{2}$	1000
			4034.49	100 R I	6d?	15	8	$2\frac{1}{2}-1\frac{1}{2}$	1000
Mn.....	2.29	$z^8P^o-e^8S$	4754.05	50 I	7	5	9	$2\frac{1}{2}-3\frac{1}{2}$	400
			4783.43	50 I	6	8	8	$3\frac{1}{2}-3\frac{1}{2}$	500
			4823.52	50 I	5	10	7	$4\frac{1}{2}-3\frac{1}{2}$	750

TABLE VI—*Continued*

Element	Excitation Potential	Multiplet	Wave-Length	Intensities: King	Intensities: Disk	Intensities: Flash	Intensities: Spot	Inner-Quantum Numbers	Height in Km
Mn....	3.06	$z^6P^o-e^6S$	6013.48	30 III	6	3	11	1½–2½	400
			6016.64	40 III	6	3	12	2½–2½	400
			6021.79	50 III	6	3	12	3½–2½	400
Na....	0.00	$3^2S-3^2P^o$	5889.96	(8 R)	30	25	95	½–1½	1500
			5895.93	(10 R)	20	20	60	½–½	1500
Na....	2.09	$3^2P^o-4^2D$	5682.67	(8)	5	2	10	½–1½	300
			5688.22	(10)	6	3	12	1½	350
Ni....	0.10	$a^3D-z^3P^o$	3492.97	150 R II	10	5	.....	2 –1	800
			3524.54	200 R II	20	12	.....	3 –2	800
			3597.70	50 R II	8	4	.....	1 –1	600
Ni....	3.3	$z^5D^o-e^5F$	4401.55	30 III	2	4	4	4 –5	400
			4462.46	10 III	1	1	1	1 –2	350
			4470.49	15 III	2	2	2	2 –3	400
Ti.....	0.02	$a^3F-x^3F^o$	3729.77	50 r I	3	3	.....	2 –2	400
			3741.06	60 r I	4	4	.....	3 –3	500
			3752.87	80 r I	4	4	.....	4 –4	400
Ti.....	0.82	$a^5F-y^5F^o$	4512.74	40 II	3	2	6	4 –5	450
			4518.03	50 II	3	2	6	3 –4	400
			4534.78	60 II	4	3	7	4 –4	400
Ti.....	1.87	$a^3G-z^3H^o$	5953.16	30 II	1	3	6	5 –6	400
			5965.83	30 II	2	3	6	4 –5	400
			5978.54	25 II	1	2	6	3 –4	350
Ti.....	2.24	$a^3H-z^3H^o$	4742.80	20 III	1	1	3	4 –4	300
			4758.13	25 III	1	2	3	5 –5	350
			4759.28	25 III	2	2	4	6 –6	350
V.....	0.28	$a^6D-y^6D^o$	4099.80	60 I	2	3	3	2½–3½	500
			4111.79	100 R I	4	5	6	4½–4½	450
			4115.18	60 I	3	4	4	3½–3½	450
V.....	1.05	$a^4D-z^4P^o$	6039.69	25 I	0	0	6	2½–2½	300
			6081.42	25 I	0	0	7	1½–1½	300
			6090.18	50 I	2	2	8	3½–2½	300

are evident: (1) greater strength in the flash than in the sun for lines of low excitation potential; (2) greater intensities corresponding to greater heights, (3) higher values of King's temperature class with increase of excitation potential.

The information from the elements *Mn*, *Cr*, and *Ca* is especially worthy of note. The lines in *Mn* for each of the three multiplets

considered all have approximately the same Rowland intensities but differ remarkably in the flash intensities. The $a^7S - z^7P^o$ multiplet of *Cr*, with the great intensities of the lines of the flash spectrum, is specially interesting. The great strength and the great height of the ultimate line of *Ca* at λ 4227 are too well known to need further comment.

Photographs of the flash spectrum taken without a slit give the possibility of estimating on a uniform scale the intensities attained by lines at different heights above the photosphere. For all of the stronger lines of the flash spectrum the author has made such estimates at three different heights: (1) at or near the photosphere, (2) at 500 km, and (3) at 1000 km, above the photosphere. These estimates taken in connection with the material in Table VI show unmistakably that the lines of small excitation potential have a smaller density gradient than is found for the lines of high excitation potential. In other words, lines of high excitation potential being produced under conditions of higher temperatures and pressures than is the case with lines of low excitation potential, the atoms of such multiplets are more concentrated toward the photosphere than is found for the atoms involved in multiplets of low excitation potential. In fact, the distribution of the latter approximates that of the enhanced lines.

It has generally been assumed that the temperature gradient plays the principal rôle in explaining these peculiarities, while the changes of pressure in the neighborhood of the photosphere play an unimportant part; and this in spite of the fact that it is generally admitted that the drop in temperature near the photosphere is probably very slight while, on the other hand, there are marked decreases of pressures with increases in height in the chromosphere. In a following publication these matters will be discussed in greater detail and comparisons will be made with various theoretical laws.

Let us return to Table IV to the peculiar agreement in values for intensity n in the violet and $n+2$ in the red. On account of the greater purity of the material we shall confine attention to the unblended lines. We shall further assume that the average heights, excitation potentials, and numbers of active atoms, in accordance with the conclusions just reached, are the same for intensity 0 to

the violet of λ 4900 as for those of intensity 2 to the red of this wavelength, the differences being due to accidental errors. Combine the values together, weighted first, according to the number of lines for which heights are known from the flash spectrum, and, second, according to the number of lines for which excitation potentials are known. Do the same for intensity 1 in the violet and 3 in the red, 2 and 4, and so forth. As the excitation potentials for lines of intensities 8, 9, and 10 in the red are nearly equal, combine these lines together, and then further combine them with intensity 6 in the violet. Intensity 0 in the red we shall call intensity -2 in the violet, and 1 in red we shall regard equivalent to -1 in the violet. The values so combined are given in Table VII, and they represent the average values of the heights and excitation potentials corresponding to each value of the Rowland intensity at an average wavelength of about λ 4200. Now multiply each value of the height for a given intensity by the corresponding value of the excitation potential for the same intensity, the products being given in the table as indicated. When the lines involved are sufficiently numerous so that they represent average conditions, then we derive the curious fact that the product of the heights in kilometers multiplied by the excitation potential in volts is a constant, no matter what the Rowland intensity. The product weighted according to the number of lines for which heights are known from flash spectra (there being a total of 700 lines) is 1218.63, and according to the number of lines of known excitation potentials (489 lines) is 1231.62.

From the material involving "all lines" of *Fe* in Table IV, similar products were formed. The constant from 1192 lines of heights from flash spectra is 1231.38, and from 831 lines of known excitation potential the value is 1245.96. The mean of the four values of the product is 1231.90.

There is another curious relationship found to exist between heights, excitation potentials, and Rowland intensities. If intensities are called R, then heights from flash spectrum plotted against $R^{3/2}$, and excitation potentials also plotted against $R^{3/2}$, each independently fall on a straight line. (On account of the few lines, intensities 12 and greater were excluded.) The formula for heights in kilometers is

$$h = 325 + 20.24 R^{3/2} .$$

TABLE VII

INTENSITIES, HEIGHTS, AND EXCITATION POTENTIALS

	Intensities															
	−2	−1	0	1	2	3	4	5	6	7	8	9	10	12	15–18	20–40
Heights	284	304	336	368	421	432	445	509	626	715	887	788	967	1500	1400	1627
No. of lines	37	62	74	92	98	103	82	57	34	13	15	4	9	2	7	11
Excitation potentials	3.99	3.20	3.57	3.12	3.26	2.98	2.69	2.53	2.22	1.66	1.15	0.97	0.88	0.48	1.42	0.78
No. of lines	10	23	47	67	67	71	64	50	29	13	15	4	9	2	7	11
Product of heights and excitation potentials	1133.2	972.8	1196.0	1148.2	1372.5	1287.4	1197.0	1287.8	1389.7	1186.9	1020.0	764.4	851.0	720.0	1988.0	1269.1
Heights, computed	268	305	325	345	382	430	486	551	622	700	783	871	965	......	......	......
Excitation potentials, computed	3.70	3.53	3.44	3.35	3.18	2.97	2.72	2.42	2.11	1.76	1.39	0.99	0.57	......	......	......

The values computed from the formula are given in Table VII. In similar fashion the formula for excitation potentials in volts is

$$E=3.44-0.09075R^{\frac{2}{3}},$$

the computed values being given in Table VII.

These curious relationships are true for neutral *Fe* under the condition that many lines of different excitation potentials and different heights are averaged together. For Rowland intensity 6, for instance, the average excitation potential is 2.09 volts and the corresponding height 622 km. From Table II and Figure 1, however, it is seen that for intensity 6 the heights vary from 400 to 1075 km, depending on the value of the excitation potential for the particular lines under consideration.

These interesting relations between Rowland intensities and average excitation potentials and heights suggest the idea that the heights must form as constant a system as either of the two other quantities, the estimation of intensities or the derivation of excitation potentials.

Great strides forward toward ultimate truth have been made through discussions of multiplet groups. The next step in this publication evidently will be the study of individual multiplets of neutral *Fe*.

WAVE-LENGTHS IN SUN AND LABORATORY

For several years the Allegheny Observatory and the Bureau of Standards have been co-operating in the determination of precise wave-lengths in the laboratory. Using interferometer methods, wave-lengths and atomic levels for *Fe* I have been determined by K. Burns and F. M. Walters.[1] They have pointed out that due to the fact that pressures in the chromosphere are very minute, the wave-lengths in the vacuum arc should furnish an accurate basis of comparison with solar wave-lengths in the *Revised Rowland*. By means of standards adopted at the Leiden Conference,[2] it is possible to reduce the *Revised Rowland* and laboratory wave-lengths to the same system. In the following this has been done and the differences for *Fe* I were then taken in the sense sun *minus* vacuum arc.

[1] *Publications of Allegheny Observatory*, **6**, 159, 1929.

[2] *Transactions of the International Astronomical Union*, **3**, 93, 1928.

As is well known, particularly from the work at Mount Wilson and Allegheny observatories, the differences sun *minus* vacuum arc are positive in value, or, in other words, the wave-lengths in the sun are greater than in the laboratory, the average difference being approximately that found for the relativity shift predicted by Einstein. These differences, however, have two systematic trends: (1) they increase gradually in amount from violet to red, and (2) in the same spectral region the differences sun *minus* vacuum arc are greater for intense lines than they are for weak lines. Since the shift to the red in the sun compared to laboratory depend on intensities, heights in the chromosphere, and excitation potentials, these various observed phenomena will be discussed in connection with multiplet groups.

MULTIPLET GROUPS OF IRON

In two important *Contributions from Mount Wilson Observatory* (Nos. 389 and 390) entitled "The Unit Character of Multiplets" and "Excitation Potential in Solar Phenomena," St. John discusses multiplet groups of *Fe*. In an equally important paper[1] read at the annual meeting of the Optical Society of America, Burns treats the same problem. St. John and Burns differ radically in the interpretations to be placed on the systematic differences of wave-lengths in sun and vacuum arc. The former takes the ground that the relativity shift to the red in the sun has been confirmed, while the latter is still unconvinced. Both agree, however, that within a single multiplet the difference sun *minus* vacuum arc should be a constant. St. John states:

> These assumptions (from which Ornstein and Burger, and Unsöld, independently have calculated the number of atoms involved in the formation of a spectral line) have no evident *raison d'être* unless they refer to the same body of absorbing material, and the observed equal red displacement for all lines in a multiplet puts the underlying assumptions upon a definite observational basis.[2]

For forming his conclusions St. John has utilized a total of 21 multiplets of *Fe* as follows: 9 strong multiplets in the violet with average excitation potential 1.01 volts, 4 of medium strength in the violet, with excitation potential averaging 2.7 volts, and 8 strong multiplets in the red and also with medium-sized excitation poten-

[1] *Journal of Optical Society of America*, **20**, 212, 1930.

[2] *Op. cit.*, p. 458.

tials. Burns, on the other hand, does not admit "an equal red displacement for all lines in a multiplet." He finds observationally that the more intense lines have a greater displacement than the less intense lines in the same multiplet, this being directly contrary to St. John's deductions. He voices his opinion in the following words: "It seems paradoxical to assume as a possibility that a very strong line of a multiplet can originate at a high solar level, where St. John postulates the descending movement, while a weak line of the same multiplet originates only at a lower solar level in the ascending vapor."[1]

The present writer is inclined to agree with St. John and therefore to disagree with Burns in the question of the relativity shift in the sun; he agrees with Burns and disagrees with St. John as to the unequal red displacement for different lines in a multiplet; but he disagrees with both St. John and Burns in the interpretation of the data observed within single multiplets.

Through the kindness of the Mount Wilson Observatory and Miss Charlotte E. Moore the writer was placed in possession of all the information on the multiplet groups of neutral *Fe* available at the end of the year 1929. As already explained, the wave-lengths in sun and vacuum arc were reduced to one system before the differences were taken. From these differences in the sense sun *minus* vacuum arc were then subtracted the predicted relativity shift $2.13 \times 10^{-6} \times \lambda$. For all individual multiplets, where there were enough spectral lines to make it worth while, the lines were divided into two groups: (1) those lying on the main diagonal of the multiplet, and (2) those lying on the side diagonals. Altogether 48 multiplets involving a total of 309 *Fe* lines were discussed in this manner. The results given in Table VIII are separated into three groups representing strong, medium, and weak multiplets. Means are given separately for lines on the main and side diagonals, and for these two combined into the whole multiplet. In each case are given the number of lines, the height in kilometers from the flash spectrum, and $\Delta\lambda$, which is equivalent to the difference sun *minus* vacuum arc from which is subtracted the predicted relativity shift. The unit is 0.001 A.

[1] *Op. cit.*, p. 221.

The division into main diagonal and side diagonals is essentially that of intensities, the main diagonal involving the stronger lines. In some multiplets, however, particularly those of the symmetrical type, the intensity of one line on the main diagonal may be less than those on the side diagonals. Hence another grouping of the material was made dividing the lines into strong (those that exceeded a certain average intensity) and weak lines. A table like that of Table VIII was then formed which gave results entirely similar to those given herewith.

TABLE VIII*

SYSTEMATIC DIFFERENCES IN HEIGHTS AND WAVE-LENGTHS WITHIN MULTIPLET GROUPS

E.P.	INTENSITY	MAIN DIAGONAL			SIDE DIAGONALS			WHOLE MULTIPLET		
		No.	$\Delta\lambda$	Hgt.	No.	$\Delta\lambda$	Hgt.	No.	$\Delta\lambda$	Hgt.
0.07	6–40	9	+3.0	1722	10	+1.4	1300	19	+2.2	1500
0.93	4–40	15	+2.0	1157	20	+0.5	792	35	+1.2	948
1.54	2–30	12	+2.0	1400	13	− .1	823	25	+0.9	1100
0.93	4– 8	5	+1.2	540	6	−0.6	500	11	+ .2	518
2.2–2.8	3–10	10	+0.9	625	17	−1.0	500	27	−0.3	548
2.4–3.2	1– 8	17	−0.9	497	25	−1.2	409	42	−1.1	445
2.2–2.8	1–6	27	−2.6	525	34	−2.5	518	61	−2.6	522
3.2–4.8	0– 6	40	−2.9	406	49	−2.4	361	89	−2.6	381

* The unit for $\Delta\lambda$ is 0.001 A.

It is evident from the abundant material that went into the table that the value $\Delta\lambda$ on the main diagonal for each multiplet averages greater in size than on the side diagonals. As the relativity shift is practically identical for main and side diagonals, the difference sun *minus* vacuum arc is therefore not a constant, as has been found by St. John, who based his conclusions on less observational material than is included in the present discussion. On the main diagonal are found not only stronger lines but also greater heights from the flash spectrum than appear on the side diagonals. On the main diagonal are also a relatively greater number of involved atoms than is the case on the side diagonals. Among the weak multiplets there is very little difference in values between the main and side diagonals on account of the small differences in intensities and correspondingly small differences in heights. On account of the greater differences in

intensities between main and side diagonals found in the multiplets with stronger lines, and consequently with lower values of excitation potentials, the differences in $\Delta\lambda$ and in the heights are more pronounced in the strong multiplets.

In Table VIII, if one goes vertically down the material dealing with "Main Diagonal," "Side Diagonals," and "Whole Multiplets,"

THE *Fe* MULTIPLET $a^5F-y^5D^o$

	F_5	F_4	F_3	F_2	F_1
D_4..........	3820 25 1600 .000 .0102	3887 8 800 .005 .0082	3940 4 500 .016 .0070	....	....
D_3..........	....	3825 20 1500 .000 .0098	3878 10 1000 .003 .0090	3917 5 600 .013 .0074	....
D_2..........	....	....	3834 14 1200 .002 .0094	3872 9 1000 .003 .0090	3898 5 600 .013 .0074
D_1..........	....	....	....	3840 10 1000 .003 .0090	3865 8 800 .005 .0082
D_0..........	Wave-length Intensity in sun Height in kilometers Evershed effect in sun-spots Sun *minus* vacuum arc in angstroms				3849 7 750 .006 .0078

a decrease in the values of $\Delta\lambda$ and in the heights is at once apparent. Since the values of $\Delta\lambda$ are not zero but change in sign from positive to negative, it is evident that in addition to the relativity shift there are other effects in the sun causing systematic differences in wave-lengths. From Table VIII it is seen that these effects are intimately connected with the intensities, heights, and excitation potentials of the spectral lines, and therefore with the number of atoms involved in the production of the lines in question.

For the purpose of illustrating the unit nature of multiplets both St. John and Burns independently have utilized the same *Fe* multiplet, $a^5F - y^5D^o$, with excitation potential 0.92 volts. After a thorough study of the whole problem, by comparing this multiplet with others, and then smoothing out accidental errors and getting rid of the effects of blends, the table above is adopted by the writer as his idea of this composite or ideal multiplet. The top number in each case is the wave-length, below this is the intensity (explained later), then come in order the height in kilometers from the flash spectrum, the Evershed effect in angstroms, and finally the difference in angstroms of sun *minus* vacuum arc. The relativity shift to the red is 0.0082 A, or 21 parts in 10,000,000.

Russell[1] has given the intensities making up the quintet system involving F- and D-levels. Below are tabulated his observed values,

SCALES OF INTENSITIES IN MULTIPLETS

Russell, *O*	54, 39, 33, 22, 13	15, 20, 17, 15	6, 8, 8
Russell, ½*O*	27, 20, 16, 11, 7	8, 10, 9, 8	3, 4, 4
Rowland	25, 20, 10, 8, 10	7, 8, 6, 7	5, 5, 5
Composite	25, 20, 14, 10, 7	8, 10, 9, 8	4, 5, 5

O, derived from King's estimates. Immediately below are the values ½*O*, and then follow the intensities from Rowland. The intensities adopted for the composite multiplets are given in the fourth line. They are virtually the mean between the value ½*O* and Rowland, but rounded off. The Rowland intensities for the three weakest lines are greater and for the next four are less than the values ½*O*.

We have already come to the conclusion that the underlying cause for explaining the intimate correlations existing between intensities, heights, and Evershed effect is to be found in the numbers of atoms, or "fictitious resonators," involved; for the flash spectrum the atoms are emitting and for the Fraunhofer spectrum they are absorbing radiation. Hence when the numbers of atoms forming any spectral line of a multiplet of any element (like neutral *Fe*) are greater than those involved for any other line, then the first line is stronger than the second and it reaches a greater effective level. It appears, therefore, that one explanation, and one only, is required

[1] *Proceedings of the National Academy of Sciences*, **11**, 326, 1925.

to clarify many of the problems connected with solar radiation. This one underlying cause is the number of atoms involved.

In the composite multiplet of *Fe*, $a^5F-y^5D^o$, the numbers of fictitious resonators effective in forming the different spectral lines vary greatly. According to Russell,[1] more than one hundred times as many atoms are active in producing the strongest line of the multiplet at λ 3820 as go to form the weakest line at λ 3940. Hence within a single multiplet one should expect that the heights found directly from the flash spectrum, or indirectly from sun-spots, would not be constant but would be greatest for the largest numbers of atoms.

It must be emphasized again and again that the "effective height" above the photosphere at which a line in the Fraunhofer spectrum is formed, the heights from eclipse spectra and the heights from the Evershed effect do not and cannot refer to the maximum heights to which atoms are ejected by solar activity. All three heights are derived from photographic plates; all depend on the effects produced by the atoms on the photograph. As already stated in the foregoing, the atoms must be in sufficient numbers, or have a concentration adequate, to leave a trace of their action on the photographic plate. It is not impossible that under average conditions of solar activity all *Fe* atoms, no matter what their atomic levels are, or whether they are neutral or enhanced, reach about the same maximum heights in the chromosphere. If the solar activity becomes greater, as in the course of the sun-spot cycle, or locally, as in prominences, the heights become greater.

The conditions under which atoms in the chromosphere radiate to form the flash spectrum (or absorb radiation in the dark-line spectrum) are becoming well understood. They depend on temperature, pressure, and concentration of atoms. Saha's theory has explained the great heights attained by the enhanced lines. If "forbidden" lines are ever found in the chromosphere, which seems improbable,[2] they should be detected at even greater heights than the ordinary enhanced lines.

For a single multiplet it is obviously necessary to assume that all

[1] *Ibid.*

[2] Eddington, *Monthly Notices of the Royal Astronomical Society*, **88**, 134, 1927.

of the spectral lines are formed under nearly identical conditions of temperature and pressure and that all the atoms reach the same maximum heights. The lines differ greatly the one from the other in the number of atoms involved in the emission (or absorption) of radiation. Let us now confine our attention to two lines from a multiplet, the one produced by one hundred times as many atoms as the other. Consider for each line a cylinder of unit cross-section. The base of each cylinder we shall call the "photosphere," each axis being perpendicular to the solar surface. The top of each cylinder is at the same great distance above the photosphere. The atoms are most concentrated near the photosphere. Looking down into the axis of each cylinder, that is, observing a spectral line at the center of the sun's disk under the ordinary conditions of the Fraunhofer spectrum, it is possible to see down into each cylinder until the atoms become so concentrated that they virtually form a black wall through which vision cannot penetrate. This black wall in each case then becomes the effective height above the photosphere at which each spectral line is formed. The stronger line of the two, the one involving the greater number of atoms, has its effective level, or takes its origin, at a greater height above the photosphere than the weaker line of fewer atoms. The foregoing expresses in non-technical language what various authorities for a number of years have been stating in technical terms. This simple scheme seems adequate to explain a great variety of solar phonomena. In particular, it seems easy to understand that within a single multiplet the spectral lines take their origin at different effective heights, the strongest lines at the greatest heights and the weakest at the least heights above the photosphere.

In comparing two lines of the same element near each other in the spectrum of the same Rowland intensity, say 6, but differing in excitation potentials, it is evident from the foregoing that relatively greater numbers of atoms are involved in the line of low excitation potential, while there is less concentration toward the photosphere of the atoms involved than is found in the line of high excitation potential. Hence, looking into the cylinders of atoms, we find at the center of the sun's disk two lines of intensity 6, of low and high excitation potential, respectively. It is evident that the effective

level is closer to the photosphere for the line of high excitation potential. Hence in this way we can readily explain the peculiarities of the lines of *Mn*, *Cr*, etc., given in Table VI, and also the reason why *Fe* lines of intensity 6 in Rowland belonging to multiplets of excitation potential 0.07 volts have heights above the photosphere of 1075 km, while lines of the same intensity but of high excitation potential are found at heights which average only 400 km.

Through a splendid series of researches carried out with great care at Mount Wilson and elsewhere, a very imposing structure has been built on the assumption that Fraunhofer lines do indeed take their origin at different heights above the photosphere. It seems entirely unnecessary to overthrow this beautiful edifice by requiring that all lines in a multiplet, no matter how much they differ in intensities, must all be found at identically the same heights. It seems equally unnecessary to assume that all lines in a multiplet, involving as they do very different numbers of atoms, must all exhibit the same difference in wave-length between sun and vacuum arc. In the composite multiplet $a^5F - y^5D^o$ on page 176 the intensities of the strongest and weakest lines of the multiplet are as 25:4 or 6:1; the heights are approximately as 3:1; and the differences sun *minus* vacuum arc are as $1\frac{1}{2}$:1. The three representations of the same composite multiplet adopted by the author, by Burns,[1] and by St. John[2] all agree well with one another in observational details.

From his discussion St. John finds that the strong solar lines show a greater red shift than do the weaker lines except in the case where strong and weak lines occur in the same multiplet, and then the red shift must perforce be the same for all lines no matter how much they differ in intensities! On the other hand, both Burns and the writer find the greater shift for the strong lines even though the strong and weak lines belong to the same multiplet. Burns attempts, without much success, to explain the greater red shift of the strong lines as due to an "intensity equation" partly due to instrumental causes. Both Burns and St. John find fault with the heights from the flash spectrum in that these heights are not a constant for all of the spectral lines of a multiplet.

The investigations by Unsöld[3] on line contours have been of the

[1] *Op. cit.*, p. 221. [2] *Op. cit.*, p. 456. [3] *Loc. cit.*

very greatest assistance in astrophysical problems. Until fuller observational verification is obtained his method must be regarded as a satisfactory first approximation. In examining the wings of certain Fraunhofer lines, however, his curves reveal the fact that the computed and observed contours do not make a precise fit. In the contours of doublets it is noticed that the precise "fit" occurs at a larger residual intensity, r, for the stronger component than for the weaker. For instance, in dealing with the H and K lines of Ca^+, the intersection of the theoretical and observed curves take place at $r=0.55$ for the H line, whereas the intersection occurs at about $r=0.68$ for the K line. To put the matter in another way, the wings of the K lines are too narrow with respect to those of the H lines. At $r=0.7$, the width of the K line is actually only 1.31 times as great as the width of the H lines, whereas according to Unsöld's model we should expect it to be $\sqrt{2}$, or 1.41 times as great. One satisfactory explanation would seem to be that actually we are seeing deeper into the reversing layer in the wings of the H line than in the wings of the K lines.

It may well be objected that the H line is distorted by the superposition of $H\epsilon$, in its center and redward wing. But a consideration of the contours of Hδ and $H\zeta$ in Unsöld's paper on the Balmer series in the solar spectrum[1] leads to the conclusion that the contour of the H line more than 2 A to the violet of its center is unaffected by $H\epsilon$. But this portion of the line shows the effect mentioned quite clearly. Moreover, the same effect is evident in the other doublets measured by Unsöld.

In these two strong lines of Ca^+ the number of contributing atoms are in the ratio of 2:1. In certain *Fe* multiplets, however, such, for instance, as the adopted composite multiplet, the ratio of the number of atoms effective in the formation of two lines in the multiplet may differ as much as 100:1. Hence, as a direct consequence of the Unsöld theory we seem forced to conclude that even within a multiplet where large ranges in intensities between different spectral lines are met we see down into the chromosphere to different distances. In other words, the stronger lines have a higher effective level than the weaker lines, or the height above the photosphere is greater for the strong lines. Within a multiplet there must be therefore a close

[1] *Ibid.*, **59**, 359, 1930.

correlation between intensities and heights, the strongest lines extending to the greatest heights.

In view of the foregoing considerations, it seems unreasonable to expect that within a multiplet the difference in wave-lengths between sun and vacuum arc should be a constant. In Table VIII it has been shown that this constancy does not exist. The individual multiplets contributing to the averages given in this table exhibit pronounced systematic differences between the main and side diagonals, particularly in the multiplets involving strong lines, or those of low excitation potential. Two strong multiplets of *Fe* are specially interesting, namely, $a^5D - z^5D^o$, with average excitation potential 0.07, and $a^5F - y^5D^o$, with excitation potential 0.92 (the composite multiplet chosen). These two multiplets have the same maximum Rowland intensity of 20 in each case, and nearly the same minimum intensity, 6 and 5, respectively. Moreover, the two multiplets cover approximately the same spectral region, λλ 3824–3930 and λλ 3820–3940, respectively, and hence no systematic effects depending on wave-length need be considered. Although the Rowland intensities average the same in the two multiplets, there are pronounced differences in the other observed details. The multiplet of low excitation potential 0.07 compared with that of higher value 0.92 shows the following: (1) greater intensities in the flash spectrum, (2) greater heights, and (3) greater values of the wave-length difference sun *minus* vacuum arc. Each multiplet separately for (1), (2), and (3) shows higher values on the main diagonal than on the side diagonals. For a height of 2000 km, from the multiplet with excitation potential 0.07, the difference sun *minus* vacuum arc is +0.0135 A, which corrected for the relativity shift 0.0082 A gives a residual difference +0.0053 A.

RELATIVITY SHIFT IN THE SUN

Long years of intensive study in the laboratory of the spectrum of iron has resulted in a splendid series of researches culminating in the precise wave-lengths given by Allegheny Observatory and the Bureau of Standards. Certain specifications have long been adopted for the construction of the arc itself in order to insure constant conditions for the production of spectral lines. After dividing the iron lines into classes as to temperature and pressure and after finding

excitation potentials, it has been tacitly assumed that the conditions necessary for the formation of spectral lines in laboratory and sun are nearly identical. For the pressure it is possible to assume that conditions in the vacuum arc may not differ radically from those found in the chromosphere, but for temperatures it is generally taken for granted that the minimum temperatures in the neighborhood of the sun are greater than the maximum possible in the arc. As a knowledge of temperature conditions is of prime importance in obtaining information about atomic levels, a note of warning must be sounded against assuming identical conditions in laboratory and sun. It is the only method available, however, but that does not necessarily mean that the interpretations are correct.

Before much further progress is made in comparing wave-lengths in sun and laboratory we need to have other elements than *Fe* investigated in order to derive from laboratory experiments a system of wave-lengths of high precision from lines of many elements produced under conditions approximating those found in the sun.

In the foregoing it has been shown that wave-lengths in sun are greater than those in vacuum arc, the average difference being approximately that of the Einstein relativity shift $2.13 \times 10^{-6} \times \lambda$. In Table VIII the residuals are given for the means of 309 lines of *Fe* after applying the relativity correction to the differences sun *minus* vacuum arc. As shown in the preceding pages, the residuals depend on the effective height above the photosphere at which the different spectral lines take their origin.

Several attempts have been made to explain these residual differences. The most notable investigation is that of St. John and Babcock,[1] and more fully elaborated by St. John.[2] It has been assumed that the positive and negative residuals represent a Doppler shift, and in consequence the atoms forming the strong lines at great heights above the photosphere are falling toward the photosphere, while on the contrary the atoms forming the weak lines of less heights are ascending from the solar surface. To this very interesting hypothesis E. A. Milne takes exception[3] and points out various difficul-

[1] *Mt. Wilson Contr.*, No. 278; *Astrophysical Journal*, **60**, 32, 1924.

[2] *Mt. Wilson Contr.*, No. 348; *Astrophysical Journal*, **67**, 195, 1928.

[3] *Monthly Notices of the Royal Astronomical Society*, **86**, 597, 1926.

ties. He himself advances the hypothesis of an asymmetrical distribution of velocity among the velocities of agitation of the individual atoms. Burns[1] favors Milne's point of view. The present writer believes that the simplest explanation is to be found in the St. John–Babcock interpretation, which is nothing more or less than a circulation of *Fe* vapor in the chromosphere. On account of the higher temperatures and higher pressures near the photosphere, the solar activity causes the *Fe* atoms to ascend through the medium of thousands of weak lines of high excitation potential, the maximum velocity found from flash spectrum for *Fe* being 0.2 km per second. The heights to which the *Fe* atoms are ejected are much greater than can be measured by the lines in the flash spectrum. In the upper reaches of the chromosphere, especially where the pressures are minute, some of the atoms lose an external electron and become ionized. From a law of nature that "whatever goes up must come down" the *Fe* atoms descend from the maximum heights. In their descent some of the ionized atoms gain an external electron and again become neutral. At less heights the atoms descend through the medium of comparatively few lines of great strength but of low value of the excitation potential. At the greatest heights observed for *Fe* lines in the flash spectrum the velocity is 0.4 km per second. In this interpretation it seems possible to adopt the St. John–Babcock suggestion that the atoms which are ascending exhibit themselves over the small bright granules shown on direct solar photographs and the descending atoms over the large dark interspaces, the observed effect being naturally an integrated one.

From the *Fe* lines given in Rowland with the Russell calibration of the Rowland intensity scale, and from the residual velocities given in Table VIII, it is possible to make a calculation of the number of atoms crossing a given level per second of time in their ascents and descents. For obvious reasons this calculation cannot be very complete. We do not know the whole *Fe* spectrum, particularly at the ultra-violet end, etc. Hence it might be expected that a rough calculation carried out under these assumptions will show more descending atoms than ascending ones. By making certain plausible assumptions (the details of which need not be stated) it has been found

[1] *Loc. cit.*

that for every 1000 atoms sinking down past a given level per second there are 700 atoms rising.

In *Mount Wilson Contribution* No. 348 St. John gives the details for *Fe* lines both at the sun's center and limb. If the interpretation as Doppler effect is correct, then at the sun's limb the motion in the line of sight of the solar vapors should be 0. The material given in St. John's Tables VIII and IX has been re-reduced, using values of wave-lengths corrected to the system of the Leiden Conference. In Table IX of this article the spectrum is divided into two regions. violet and red. The uncorrected values are those of St. John, Manifestly, the values $\Delta\lambda$ are not 0. As a whole, the corrected values

TABLE IX

IRON LINES AT THE SUN'S EDGE

Wave-Length	Intensity in Multiplet	No. of Lines	Corrected $\Delta\lambda$	No. of Lines	Uncorrected $\Delta\lambda$
3787–3907	8–25	17	+1.7	17	+2.2
3790–3896	5– 7	14	+1.6	14	+1.7
3789–3898	3– 4	13	+1.2	21	+0.6
3789–3898	0– 2	9	−1.0	18	−0.1
5049–5507	5– 7	13	+3.6	13	+3.2
4994–5456	3– 4	22	+5.8	27	+3.1
5028–5567	0– 2	9	+2.0	23	+0.2

* $\Delta\lambda$ (unit, 0.001 A) = wave-length difference sun *minus* vacuum arc from which is subtracted the predicted relativity shift.

at the sun's limb given in Table IX are greater in size than the corresponding values for the same intensities on the sun's disk given in Table VIII. In Table IX for the same intensities the values of $\Delta\lambda$ at the red are greater in size than in the violet. This difference between red and violet is another illustration of the difficulty of securing precise wave-lengths at the sun's edge where there are large limb effects. On account of the small number of lines that enter into Table IX it is necessary to conclude that its tabulated results neither affirm nor deny the relativity shift.

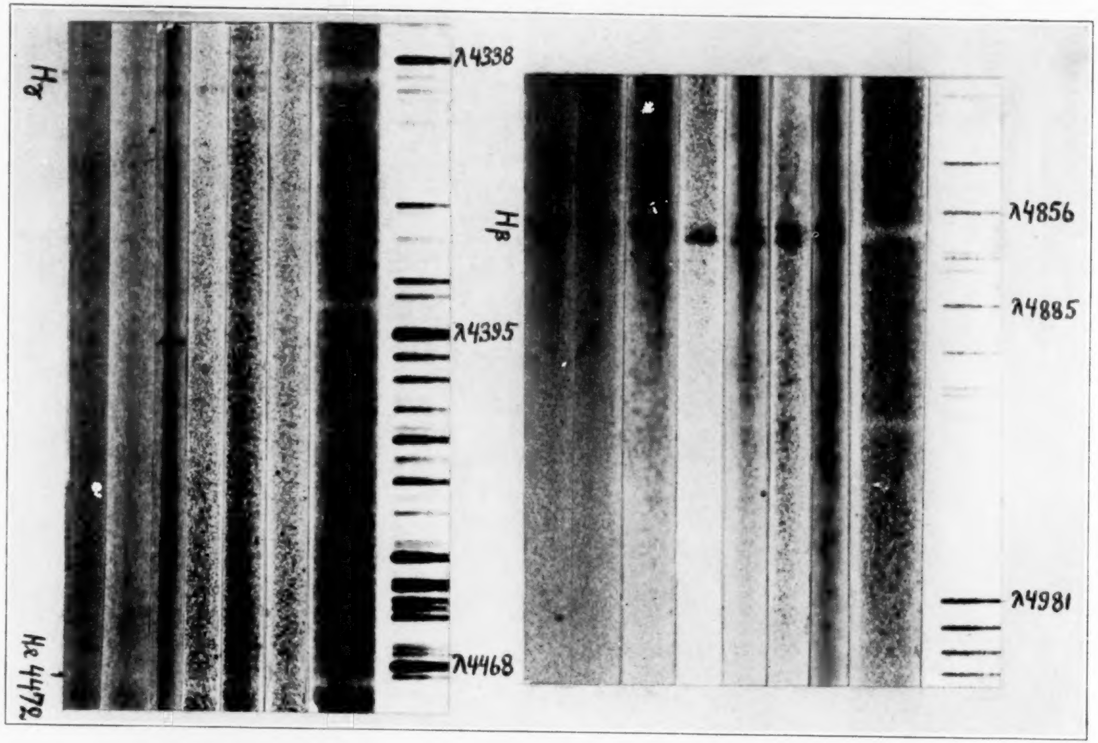
The number of atoms that contribute to the formation of a spectral line in a radial direction at the sun's center are very different from the numbers met in a tangential direction at the sun's edge. It would appear that the relatively greater number of contributing atoms for a line at the sun's edge would simulate condi-

tions at greater heights than are found for lines of like intensity in the radial direction, and hence it might seem plausible to assume that $\Delta\lambda$ in Table IX need not necessarily be 0, but on the contrary should be a small positive quantity. For 53 lines in the violet the mean value is +0.0010 A, but from 44 lines farther to the red it is +0.0044 A. However, as already stated, the accidental and systematic errors in wave-lengths at the sun's edge are large. On account of the small number of lines the results in the table appear to have little meaning.

I am greatly indebted to Emma T. R. Williams for valuable assistance and helpful suggestions rendered throughout the present discussion.

LEANDER McCORMICK OBSERVATORY
August 1, 1930

PLATE XI



Changes in Relative Intensities of Hydrogen Emission Components of π Aquarii

See p 348

NOTE ON THE VARIABLE LINES OF HYDROGEN IN THE SPECTRUM OF 52 Π AQUARII

By CHARLES D. HIGGS

ABSTRACT

Reproductions of spectra of π Aquarii are shown, exhibiting the variability of spectrum characteristic of B_e stars.

Measurements of radial velocities of components of bright H lines are shown. Attempts to correlate the separations of these, or their velocity shifts, with the variations in intensity, or to establish a period for the latter proved futile. The scattering would seem to be due mainly to photographic effects.

Contours of some of these lines are reproduced, and the bibliographical and observational record of π Aquarii is included.

The late R. H. Curtiss believed variability of spectrum to be the prevailing attribute of stars of spectral type B_e[1]. He found, out of seventeen stars with double $H\beta$ or $H\gamma$ emission, for which he had a long series of plates, that eleven were variables of the type of ϕ Persei. He also noted that the changes in the emission components were accompanied by synchronous alterations in wave-length.

An examination of some recent spectrograms of 52 π Aquarii ($\alpha = 22^h 20^m$; $\delta = +0°52'$ [1900]; vis. mag. = 4.64; sp. = Blp) taken at the Yerkes Observatory, leading to a comparison with earlier Yerkes plates of that star, evidences very strikingly the type of variation of which Curtiss spoke. This star seems to offer a particularly good illustration of this balanced shifting of intensity from one component to the other, through a phase of symmetrical equality (see Plate XI).

Figure 1 illustrates contours of some of these lines at opposite phases, as reduced from the microphotometric tracings, which are shown in the upper right corner. After allowances are made for the rather arbitrary placing of the line of the continuous spectrum, it is noticeable that the separations of the components and the widths of the lines are quite similar. The maximum intensity attained by the violet or the red component at opposite phases is very nearly the same, and the total amount of emission is approximately constant at all phases.

[1] *Popular Astronomy*, **33**, 357, 1925.

In Table I is a list of the Yerkes plates of π Aquarii with estimates of the apparent relative intensities and of the measures of the radial

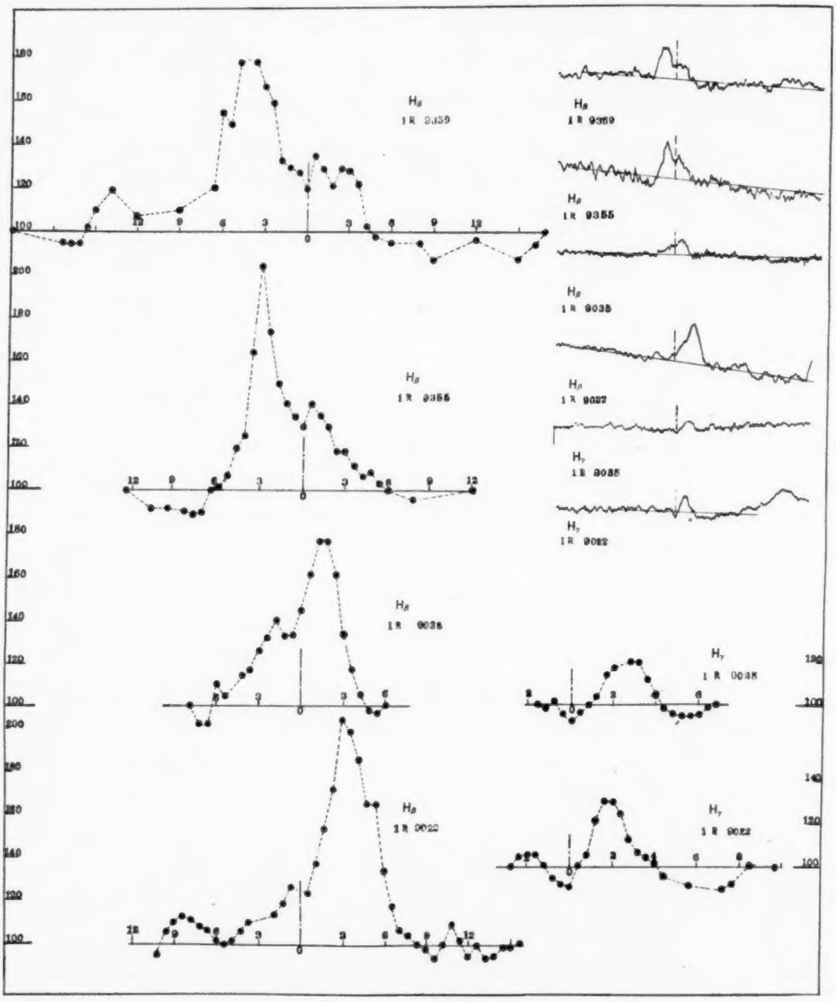


FIG. 1.—Line contours of π Aquarii

velocities for $H\beta$. The measurements in Table I show no definite correlation between the separation of the components and their relative intensities. There is a very evident shift of the mean of the measurements of the two outer edges of the emission components,

but this is doubtless due to photographic spreading on the part of the stronger of the components. The more intense one will encroach upon the central absorption at the expense of the weaker, and there results a displacement in wave-length which is really only photographic.

The mean radial velocity from the measures of the central absorptions is −8 km/sec. The mean velocity from the bright-violet components is −126 km/sec.; from the bright-red components is

TABLE I

Date G.M.T.	Rel. Int.	Radial Velocity			Plate Taken By
		Violet Comp.	Cent. Abs.	Red. Comp.	
1915 July 9.88	$R>V$	−100	+10	+95	B, S
1915 July 16.81	$R>V$	150	−7	151	B, S
1915 July 30.85	$R>V$	144	−11	112	B, S
1915 Aug. 6.75	$R=V$	99	−34	42	B, S
1919 Oct. 3.66	$R=V$	128	−6	168	B, Bk, S
1919 Oct. 17.53	$R=V$	167	−13	107	B, Bk, Pv, S
1919 Oct. 31.65	$R=V$	124	+23	160	Pv, S
1919 Nov. 14.48	$V>R$	134	−33	74	B, Bk
1919 Nov. 14.52	$V>R$	94	+9	140	B, Bk
1919 Nov. 17.52	$R=V$	107	+17	124	Pv, S
1928 Sept. 16.31*	$R>>V$	133	−44	74	Lv, S
1928 Sept. 20.14*	$R>>V$	394†	....	159†	P, S
1930 May 10.39*	$V>R$	−220†	....	+277†	σ, S

Observers: B=S. B. Barrett, S=F. R. Sullivan, Bk=Miss D. Block, Pv=J. Paraskevopoulos, Lv=C. T. Elvey, P=A. Pogo, σ=O. Struve.

* U.T.

† Measures of outer edges; centers of components unmeasurable.

+113 km/sec. The mean width of the whole emission line (red edge of red component to violet edge of violet component) is 7.55 A, which is in excellent agreement with the value of 7.42 A obtained by Curtiss.

Following is the bibliographical and observational record of π Aquarii, so far as I have been able to collect it from the date of discovery as a bright-line star by Miss Maury in 1890 down to the present. It is noticeable that with the exception of Curtiss' statement, above mentioned, there is no record of the star's variability of spectrum. The Yerkes series starts in 1915. It would be interesting to ascertain if the present type of change is a recent develop-

ment of the star's history, or whether the observational record of the previous twenty-five years shows a similar behavior.

E. C. Pickering, in *Report IV of the Draper Memorial*, in 1890, announced discovery by Miss A. C. Maury, who noted bright $H\beta$.[1]

W. W. Campbell, *Astrophysical Journal*, **2**, 3, 1895, noted bright $H\alpha$.

A. C. Maury, *Annals of Harvard Observatory*, **28**, 93, 101, 1897: Doubly reversed H lines.

Mrs. W. P. Flemming, *ibid.*, **56**, 183, 1912: Bright H lines.

P. W. Merrill, *Lick Bulletin*, **7**, 162, 1912: $H\beta$ double bright, unsymmetrical with $V > R$; $H\gamma$ wide bright.

W. J. S. Lockyer, *Monthly Notices of the Royal Astronomical Society*, **84**, 421, 1923: $H\beta$, $H\gamma$, $H\delta$, well-defined double bright on wide absorption; $V > R$.

R. H. Curtiss, *Publications of Detroit Observatory*, **3**, 8, 1923: Estimated widths of lines for $H\beta$, $H\gamma$, $H\delta$, from observations in 1911.

Merrill, Humason, and Miss Burwell, *Astrophysical Journal*, **61**, 401, 1925: Notes $H\alpha$ bright, but is not included in list of spectrum variables.

R. H. Curtiss, *Popular Astronomy*, **33**, 537, 1925: Listed as a ϕ Persei variable and period of 2000 d. assigned.

W. J. S. Lockyer, *Monthly Notices of the Royal Astronomical Society*, **85**, 594, 1925: Listed among stars with predominance of Fe^+ lines.

E. B. Frost, S. B. Barrett, O. Struve, *Astrophysical Journal*, **64**, 17, 1926: Included in "Radial Velocities of 368 He Stars"; $V = +2{:}8$ km/sec.

P. W. Merrill, *ibid.*, **65**, 290, 1927: Listed as a "normal" B_e; bright Fe^+ lines.

R. H. Curtiss, *Popular Astronomy*, **37**, 579, 1929: Pronounced variability; period revised to 2700 d.

It is, perhaps, not generally realized that there are two distinct types of variation in the emission lines in B_e spectra: (1) They have been known to appear, or to disappear, in stars where not previously so observed (as in the case of Pleione). (2) There is a variation of the relative intensity, the total emission (sum of both components) remaining approximately constant, as in π Aquarii.

Efforts to correlate the observed changes in the intensities with the period of 2700 d., given by Curtiss, proved futile, and more material will be needed to determine the period more accurately. As there is no positive evidence of any velocity shifts or changes in the separations of the components, it is hardly possible to ascribe the observed changes of intensity to revolution in a binary orbit.

YERKES OBSERVATORY
September 1930

[1] This star was listed as type F in the first *Draper Catalogue* (*Harvard Annals*, **27**, 105, 1890), but this was undoubtedly a mistake.

ABSORPTION LINES OF SULPHUR (S III AND S II) IN STELLAR SPECTRA

By F. E. ROACH

ABSTRACT

Several stellar lines are identified as due to the ion of S III. Six lines not previously measured are attributed to the ion of S II, and a number of lines already measured are corroborated. Computations have been made involving the principles of thermal ionization as affecting the intensity of absorption lines. The observed position of maximum intensity of the sulphur lines is found to agree satisfactorily with the predictions of theory, namely, in spectral classes B5 and B1 for S II and S III, respectively.

A study of the spectrum of S III as reported by S. B. Ingram[1] shows a number of the stronger lines in the region between λ 3900 and λ 4400. Since this portion of the spectrum is conveniently studied on plates taken with the Bruce spectrograph of the Yerkes Observatory, it seemed advisable to investigate the presence of these lines in stellar spectra. Sir Norman Lockyer[2] measured the lines λ 4285.1 and λ 4253.8 in stars of early class, noting their abnormal behavior, and identified them as sulphur lines. These lines have been attributed to S III by Miss C. H. Payne.[3] The line λ 4253.59, as recorded by Ingram, is given an intensity of 10. Unfortunately there is a strong oxygen line at λ 4253.98 which will blend with the sulphur line, rendering the identification uncertain. Hence, the case rests on the single line λ 4285.1, which is usually very faint in stellar spectra. In the plates examined it appears as a diffuse line suggesting that it, too, may be a blend.

For the purpose of this investigation three plates were chosen, a single-prism (1R 9307) and a three-prism (R 1771) spectrogram of 2 β Canis Majoris (B1), and a single-prism spectrogram (1R 9263) of 88 γ Pegasi (B2). The dispersion at λ 4500 is 10 A per millimeter for three prisms and 30 A per millimeter for one prism. The negatives were taken on Eastman Process plates and developed in Eastman D-11. A summary of the measurements is given in Table I.

[1] *Physical Review*, **33**, 907, 1929.

[2] *Proceedings of the Royal Society*, *A*, **80**, 50, 1907. See also F. E. Baxandall, ***Publications of the Solar Physics Committee***, 1914.

[3] *Stellar Atmospheres*, p. 207, 1925.

The first column gives Ingram's wave-lengths with the intensities in parentheses. The other columns contain the stellar wave-lengths and estimated intensities. The scale used is arbitrary, ½ indicating a

TABLE I

λ (Lab.) I.A. (Air)	2 β Can. Maj. 1R 9307	2 β Can. Maj. (1R 9307) Second Measure	2 β Can. Maj. R 1771	88 γ Pegasi 1R 9263
3928.59 (9)......	3928.67 (2)	....	....	3928.79 (2)
3983.76 (7)......	3983.81 (½)	....	....	3983.98 (½)
3985.97 (5)......	3985.53 (1)	3985.85 (1)	....	3985.91 (1)
4253.59 (10)......	4253.87 (3)	....	4253.79 (4)	....
4284.99 (8)......	4285.46 (2)	4285.46 (2)	4285.15 (2)	....
4332.72 (7)......	4332.45 (1)	....	4333.08 (1)	....
4354.57 (5)......	4353.89 (½)	4354.00 (½)	4354.43 (½)	....
4361.54 (7)......	4361.63 (1½)	4361.81 (1½)	4361.48 (1½)	....
4364.74 (5)......	4364.18 (½)	4365.30 (½)	4365.03 (1)	....

TABLE II

λ Lab. (Air) I.A. (Ingram)*	67 Ophiuchi			β Orionis R 1768
	1R 9256	1R 9262	1R 9301	
3923.43 (6)......	....	3923.53 (1)	....	This plate is not measurable to the violet of λ 4300.
3993.49 (6)......	....	3993.44 (½)	3993.45 (½)	
4028.74 (7)......	....	4028.30 (½)	4028.59 (½)	
4032.77 (6)......	....	4032.28 (½)	4032.33 (1)	
4142.24 (8)†.....	4142.05 (1½)	4142.68 (1)	....	
4145.05 (8)†.....	4145.00 (1½)	4145.25 (1)	....	
4153.05 (10)†.....	....	4153.32 (2)	4153.01 (2)	
4162.64 (10)†.....	....	4162.81 (2)	4162.76 (2)	
4267.76 (6)......	....	4267.31 (5)	(Blend with *C* II λ 4267.16)	
4294.39 (6)†.....	....	4294.26 (½)	4294.37 (1)	....
4463.58 (7)......	....	....	....	4463.60 (½)
4464.44 (6)†.....	....	....	....	4464.43 (½)
4483.42 (6)......	....	....	....	4483.30 (1)
4524.96 (6)†.....	....	....	....	4524.86 (1)
4716.25 (7)†.....	....	....	....	4716.48 (1½)

* *Physical Review*, **32**, 172, 1928. † Also identified by Lockyer in β Orionis.

line, the reality of which is uncertain, and 1, a line present but very faint. Higher figures represent successively stronger lines.

There is positive evidence that λ 4253.59 is a blend with *O* II λ 4253.98. A. Fowler[1] gives for the *O* II line a laboratory intensity of 8, the same as for *O* II λ 4185.45 and *O* II λ 4317.16. The stellar intensity of λ 4253 is decidedly stronger than of these latter lines.

[1] *Proceedings of the Royal Society*, A, **110**, 476, 1926.

From three plates measured by Dr. Struve he finds the following wave-lengths: $\lambda\lambda$ 4253.61, 4253.62, 4253.90. The mean value, together with the writer's measures, is λ 4253.76. These facts indicate that this line is a blend, *S* III and *O* II being about equally strong.

A systematic search for the stronger lines of *S* II revealed a few not heretofore identified and corroborates the early work of Lockyer.[1] Three single-prism spectrograms of 67 Ophiuchi (B5p) and one of a dispersion of three prisms of β Orionis (B8p) were utilized. The observers were Messrs. Struve, Higgs, and Keenan. A summary of the result is shown in Table II.

The line λ 4267 is probably due to a blend of the carbon and sulphur lines in types B3 and B5. It has been measured on a number of Yerkes spectograms by Dr. Struve and by the writer and the average values for the various spectral types are:

Spectral Type	Average Wave-Length
B0	4267.02
B1	4267.01
B2	4267.13
B3	4267.27
B5	4267.28

In the earlier types the value is nearer the wave-length of the carbon line λ 4267.16 while in the later types the weight of the blend with *S* II λ 4267.76 tends to give a higher value to the wave-length. Carbon appears to be the stronger of the two components.

It is of interest to apply theoretical considerations of thermal ionization to the problem of line intensities. Computations have therefore been made according to the older equations of R. H. Fowler and E. A. Milne,[2] employing fractional concentrations, as well as with the more recent equations of Milne[3] involving the "number of atoms" in a given excited state. The derivations of these equations will not be reproduced. The fundamental assumption states that the intensity of a given spectral line is a function of the number of atoms capable of absorbing the radiation in question.

Let n_r represent the fraction of the total number of a particular kind of atom in a given state of excitation, r. This is given by

$$n_r = f_r(1-x) , \tag{1}$$

[1] See p. 191, n. 2.

[2] *Monthly Notices*, **83**, 403, 1923; **84**, 499, 1924.

[3] *Ibid.*, **89**, 17, 1928.

where $(1-x)$ is the fraction of the atoms in the neutral state and f_r is the portion of the neutral atoms in the excited state. The fraction of the atoms which are neutral is given by

$$1-x=\frac{b(T)}{b(T)\delta+aT^{5/2}e^{-\chi_1/kT}}, \tag{2}$$

where $b(T)$ is the partition function;

$$a=\frac{.332\sigma}{P_e};$$

P_e is the average partial electronic pressure; σ, the symmetry number of the atom (number of spectroscopic valency electrons); T, the absolute temperature; k, Boltzmann's constant $=1.37\times 10^{-16}$; and χ_1, the ionization potential.

The fraction of neutral atoms in the excited state is given by the expression

$$f_r=\frac{q_r e^{-(\chi_1-\chi_1^{(r)})/kT}}{b(T)}, \tag{3}$$

where q_r is the statistical weight of the excited state and $[\chi_1-\chi_1^{(r)}]$ is the excitation potential.

These formulae apply to the case of atoms once or twice ionized when the appropriate ionization and excitation potentials are used. Figure 1 shows the variation of the logarithm of n_r with the absolute temperature. It will be seen that the maxima of these curves come at about 15,000° and 21,000° for S II and S III, respectively. This corresponds to spectral types B5 and B1 on the scale adopted.

The more recent work of Milne gives us formulae involving the number of atoms in an excited state. If $N_0^{(r)}$ represents the number of neutral atoms in the state, r, then

$$N_0^{(r)}=A_0^{(r)}N_0\,. \tag{4}$$

$A_0^{(r)}$ is the excitation factor for neutral atoms and is given by

$$A_0^{(r)}=\frac{q_0^{(r)}}{q_0\cdot[e^{-(\chi_1-\chi_1^{(r)})/kT}}, \tag{5}$$

$q_0^{(r)}$ being the statistical weight of the state, r; q_0, the statistical weight of the neutral atom; $\chi_1 - \chi_1^{(r)}$, the excitation potential.

N_0 represents the number of all the atoms of the element in question which are neutral. It is defined by equation (6), which, according to Milne, applies "when the element is surrounded by an excess of atoms just once ionized."

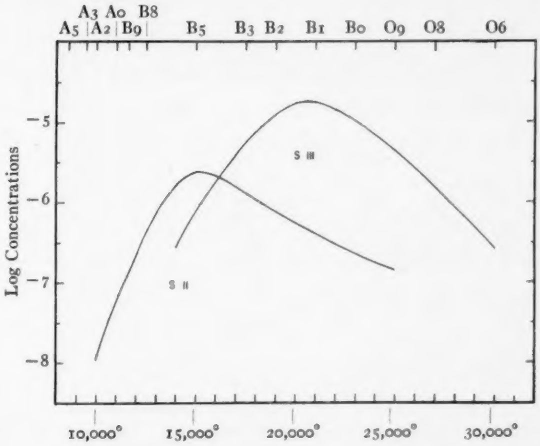


FIG. 1.—Variations of log N_r with the temperature for S II and S III

$$N_0 = 2\epsilon/mg \cdot \left[P_0 - K_1 ln\left(1 + \frac{P_0}{K_1}\right)\right], \qquad (6)$$

where ϵ is the percentage by weight of the amount of the element present; m, the mass of the atom; g, the average acceleration due to gravity; P_0, the partial electronic pressure at the base of the reversing atmosphere; and K_1, the equilibrium constant which is given by

$$K_1 = \frac{2(2\pi m_e)^{3/2}(kT)^{5/2}e^{-\chi_1/kT}q_2}{q_1 h^3}. \qquad (7)$$

P_0 is not taken as a constant as in the older theory but is assumed to vary with the temperature according to the equation

$$P_0 = \sqrt{\frac{\tau_0\, g}{a}\left(\frac{T}{10^4}\right)^{3/2}}, \qquad (8)$$

where τ_0, the optical depth, is taken as $\frac{2}{3}$ and $\alpha = 10^{-3}$. Milne's theory puts P_0 proportional to $T^{9/4}$. In line with a suggestion of J. A. Gaunt in his article on "Continuous Absorption" appearing in the *Proceedings of the Royal Society*, **26,** 654, March 3, 1930, P_0 has been taken proportional to $T^{3/4}$. C. T. Elvey[1] finds that this value in the formulae gives curves which fit the observations for hydrogen better than those using P_0 proportional to $T^{9/4}$. This not only moves the point of maximum to lower temperatures but also causes the curve to descend more rapidly on the side of high temperature. Equations

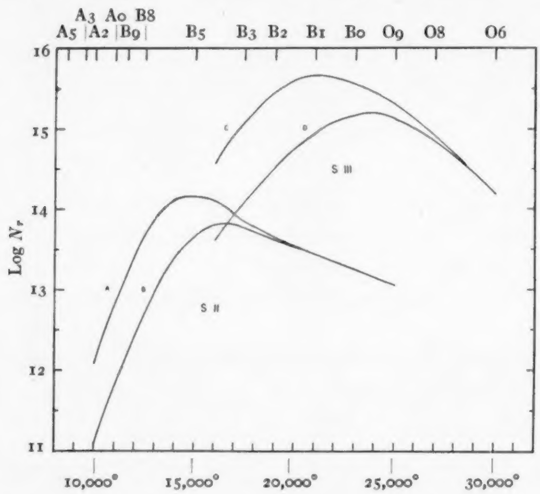


FIG. 2.—Variations of log N_s with the temperature for *S* II and *S* III. Curves *A* and *C* are for $g = 10$ and *B* and *D* are for $g = 10^3$.

(4), (5), and (6) apply to atoms once or twice ionized when the appropriate ionization and excitation potentials are used. In Figure 2 the logarithm of the number of excited atoms is plotted against the absolute temperature, according to equation (4).

A thorough examination of the Yerkes spectrograms has been made for the purpose of finding the maxima of the sulphur lines which have been identified. Very few plates are available for this. In the first place, many of the lines are at the limit of visibility even on the contrasty process plates and will therefore appear only at the point of maximum intensity. In the second place, the number of stars of class B brighter than the fifth magnitude and having good

[1] *Astrophysical Journal*, **71,** 208, 1930.

sharp lines is not large. Fainter stars require too long an exposure since the process emulsion is very slow. Table III gives a list of the plates chosen.

The plates were examined in the Hartmann spectrocomparator, a plate of 2 β Canis Majoris (1R 9307) being used to establish coincidence with the *S* III lines, and of 67 Ophiuchi (1R 9262) in the case of *S* II. Table IV summarizes the results. The series classification of the lines is from Ingram. The excitation potential is in volts.

TABLE III

Spectral Type	Star	Plate	Date Taken (U.T.)
B0	47 ρ Leonis	1R 9345	1930 April 5.2
B1	2 β Can. Maj.	1R 9307	1930 March 6.0
	44 ζ Persei	1R 9264	1929 July 27.4
	21 ϵ Can. Maj.	1R 9342	1930 April 5.0
B2	88 γ Pegasi	1R 9257	1929 July 19.3
		1R 9263	July 27.3
		1R 9299	Sept. 1.2
B3	85 ι Herculis	1R 9242	1929 July 3.3
	102 Herculis	1R 9329	1930 March 22.4
	17 ζ Cass.	1R 9269	1929 July 29.3
	45 ϵ Cass.	1R 9276	Aug. 1.3
B5	67 Ophiuchi	1R 9241	1929 July 3.2
		1R 9256	July 19.2
		1R 9262	July 27.2
		1R 9301	Sept. 2.1
	22 τ Herculis	1R 9358	1930 May 20.3
B9	11 ϕ Herculis	1R 9316	1930 March 8.4
		1R 9357	May 20.2

No attempt has been made to ascribe numerical values to the intensities of the lines on account of their uniform weakness. The symbol $\times$ in a vertical column indicates the presence of the line on one or more of the plates of the type in question. Since no single-prism spectrogram of a B8 star was available, it has been necessary to make use of the data from the Kensington plates.

A number of *S* II lines to the red of $H\beta$ were measured and identified by Lockyer, chiefly on plates of Rigel taken at Kensington. Although these lines cannot be measured on the Yerkes spectrograms, they have been included in Table IV in order to bring to-

gether in one outline all the existing identifications. The data of Table IV indicate that the maxima are in the neighborhood of B1 for *S* III and B5 for *S* II as the theory predicts.

TABLE IV

Line	Classification	E.P.	*O*	B0	B1	B2	B3	B5	B8	B9	Remarks
	S III; I.P. = 34.9 Volts										
3928.59 (9)...	$3dD_3-4pP_2$	18.2	....	×	×	×	×	×	....	....	
3983.76 (7)...	$3dD_2-4pP_1$	18.2	....	×	×	×	....	....	....	....	
3985.97 (5)...	$3dD_1-4pP_0$	18.2	....	....	×	×	....	....	....	....	
4253.59 (10)...	$4sP_2-4pD_3$	18.2	×*	×	×	×	×	×	....	....	Blend with *O* II λ 4253.98
4284.99 (8)...	$4sP_1-4pD_2$	18.1	×‡	×	×	×	....	....	....	....	Blend with *O* II λ 4285.70
4332.72 (7)...	$4sP_0-4pD_1$	18.1	....	×†	×	....	....	....	....	....	
4354.57 (5)...	$3dD_2-4pD_3$	18.2	....	....	×	....	....	....	....	....	
4361.54 (7)...	$4sP_2-4pD_2$	18.2	....	×	×	×	×	....	....	....	
4364.74 (5)...	$3dD_3-4pD_3$	18.2	....	....	×	....	....	....	....	....	
	S II; I.P. = 23.3 Volts										
3923.43 (6)...	$4pD_2-4dF_3$	16.2	....	....	....	....	×	×	×§	....	
3993.49 (6)...	$3dF_4-4p'F_4$	14.3	....	....	....	....	×	×	....	....	
4028.74 (7)...	$4pD_4-4dD_4$	15.9	....	....	....	....	×	×	×‖	....	
4032.77 (6)...	$4pS_2-4dP_3$	16.2	....	....	....	....	×	×	×¶	....	
4142.24 (8)...	$4pD_1-4dF_2$	15.8	....	....	....	×	×	×	×**	....	
4145.05 (8)...	$4pD_2-4dF_3$	15.8	....	....	....	×	×	×	×**	....	
4153.05 (10)...	$4pD_3-4dF_4$	15.8	....	×	×	×	×	×	×**	....	Blend with *O* II λ 4153.31 in early types
4162.64 (10)...	$4pD_4-4dF_5$	15.9	....	....	×	×	×	×	×**	....	
4174.25 (5)...	Unclassified	....	....	....	....	....	....	....	×**	....	
4267.76 (6)...	$4pP_2-4dD_3$	16.0	×**	×**	×	×	×	×	×**	....	Blend with *C* II λ 4267.16
4294.39 (6)...	$4pP_3-4dD_4$	16.1	....	....	....	....	×	×	×**	....	
4463.58 (7)...	$4pD_4-5sP_3$	15.9	....	....	....	....	....	....	×		
4464.44 (6)...	Unclassified	....	....	....	....	....	....	....	×††	....	
4483.42 (6)...	$4pD_3-5sP_2$	15.8	....	....	....	....	....	....	×	....	
4524.96 (6)...	$4s'D_3-4p'P_2$	15.0	....	....	....	....	....	....	×††	....	
4716.25 (7)...	$4sP_2-4pS_2$	13.5	....	....	....	×§§	....	....	×††	....	
4815.52 (9)...	$4sP_3-4pS_2$	13.6	....	....	....	×§§	....	....	×**	....	
4917.15 (2)...	$4sP_1-4pP_1$	13.5	....	....	....	....	....	....	×**	....	(Doubtful)
4925.32 (5)...	$4sP_1-4pP_2$	13.5	....	....	....	....	....	....	×**	....	
4991.94 (3)...	$4sP_2-4pP_2$	13.5	....	....	....	....	....	....	×**	....	(Doubtful)
5009.54 (4)...	$4sP_2-4pP_1$	13.5	....	....	....	....	....	....	×**	....	
5014.03 (3)...	$4sP_2-4pP_2$	13.5	....	....	....	....	....	....	×**	....	(Doubtful)
5032.41 (5)...	$4sP_3-4pP_3$	13.6	....	....	....	....	....	....	×**	....	
5453.81 (10)...	$4sP_3-4pD_4$	13.6	....	....	....	....	....	....	×‡‡	....	

* Measured by H. H. Plaskett in 10 Lacertae, also on Kensington plates of ι Orionis.

† Unidentified line at λ 4332.9 (Kensington).

‡ Measured on Kensington plates of ι Orionis.

§ Unidentified line at λ 3923.6 (Kensington) in Rigel.

‖ Line at λ 4028.74 (Kensington) ascribed to Ti.

¶ Unidentified line at λ 4033.2 (Kensington) in Rigel.

** Found on Kensington plates; not measured by writer.

†† Found on Kensington plates; also by writer.

‡‡ Measured by Keeler in Rigel (*Astronomy and Astrophysics*, **13**, 489, 1894).

§§ Found in γ Orionis (Kensington).

I wish to acknowledge the help of Dr. Struve and Mr. Elvey, who suggested this problem and offered much valuable criticism.

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THE COEXISTENCE OF STELLAR AND INTERSTELLAR CALCIUM LINES IN THE ECLIPSING BINARY U OPHIUCHI

By OTTO STRUVE

ABSTRACT

The eclipsing variable U Ophiuchi of spectral type B8 (Harvard) was photographed with the single-prism spectrograph attached to the 60-inch reflector of the Mount Wilson Observatory. Three plates taken near maximum separation of the lines show a fairly strong narrow absorption line due to interstellar calcium, between two faint and diffuse stellar components. The spectrum also reveals the presence of interstellar sodium lines. This is regarded as a further proof in favor of Sir Arthur Eddington's theory of interstellar matter.

According to Sir Arthur Eddington's theory of interstellar matter, all distant stars, regardless of spectral class, should display in their spectra "stationary" lines due to interstellar calcium and sodium. Consequently, a sufficiently distant spectroscopic binary with large relative velocity should show an interstellar K line between two stellar components. Several such cases have been suspected in the past,[1] but the evidence was generally regarded as insufficient. In order to test this I selected the eclipsing variable U Ophiuchi (α $17^{h}11^{m}.4$, $\delta+1^{\circ}19'$ [1900], var. 6.0–6.7, Harvard spectrum B8). Its spectrographic orbit had been determined by J. S. Plaskett,[2] who had found the spectra of both components present, the relative velocity (maximum separation of the lines) being 384 km/sec. Plaskett states that the calcium K line was measured as a double, but no mention is made of an interstellar line. He assigns the star to spectral class B5 and estimates its parallax at $0''.005$.

From my former results on the intensity of interstellar K as a function of distance[3] it follows that a star at a distance of 200 parsecs from the sun should show an interstellar K line of intensity 2 on my arbitrary scale. The necessary observations were made with the 60-inch reflector of the Mount Wilson Observatory. Three spectrograms were obtained near maximum separation of the lines, and all

[1] Cf. *Popular Astronomy*, **34**, 4, 1926.

[2] *Publications of the Dominion Astrophysical Observatory, Victoria*, **1**, 138, 1919.

[3] *Monthly Notices of the Royal Astronomical Society*, **89**, 567, 1929.

show interstellar K as a fairly strong, sharp, and narrow line, between two faint and diffuse stellar components. Eastman Process plates were used to obtain better contrast. The linear dispersion was 21 A/mm at λ 3933.

Dr. P. W. Merrill has very kindly obtained two plates of U Ophiuchi with his grating spectrograph, adjusted for the visual region. His measurements of interstellar D_1 and D_2 and of stellar D_3 are included in Table I. In a recent letter he states that "the sodium lines in all probability are detached."

The interstellar lines of Ca^+ and of *Na* give approximately the same radial velocity, the adopted mean being −21.0 km/sec. The

TABLE I

RADIAL VELOCITIES OF U OPHIUCHI

DATE 1930	U.T.	PHASE	INTERSTELLAR		STELLAR Ca^+		MEAN OF ALL STAR LINES	
			Ca^+	*Na*	Comp. I	Comp. II	Comp. I	Comp. II
								km/sec.
June 16	4^h06^m	0^d283					−182	+184
June 16	7 30	0.424	−19.8		−188	+162	−174	+153
July 3	4 55	0.543	26.8		−184	+160	−153	+152
July 3	6 40	0.616					−164	+124
July 4	4 05	1.508					+ 77	− 96
July 7	6 45	1.265	−16.4		+181	−185	+166	−188
July 12	6 35	1.226		−21			(+187)	
July 13	5 37	0.508		−21			−155	

component due to the motion of the solar system is roughly 17.5 km/sec.; consequently the residual velocity from the interstellar lines is −3.5 km/sec.

The spectral type of U Ophiuchi is rather difficult to estimate, since the lines are broad and diffuse. It is probably earlier than B8 since *He* 4472 is stronger than Mg^+ 4481. On the other hand, Si^+ 4128 and 4131 seem to be intermediate between *He* 4:21 and *He* 4144. This, together with the strength of the hydrogen lines and the existence of measurable stellar calcium lines, justifies its classification as B5.

As a by-product I have measured several other plates, exposed for the ordinary photographic region around λ 4500, and not showing the region near K. The measurements are given in the table. The

phases were computed from principal minimum J.D. 2418026.703 + $1^{d}6773476E$. The observations agree well with the published velocity-curve and thus confirm the period and the orbital elements.

I am greatly indebted to Dr. W. S. Adams for the opportunity to use the Mount Wilson equipment, to Dr. Sanford for the plate of July 7, and to Dr. Merrill for permission to quote his observations of July 12 and 13.

YERKES OBSERVATORY
August 3, 1930

REVIEWS

Mathematical and Physical Papers. By Sir Joseph Larmor. Cambridge University Press, 1929. Vol. I: pp. xii+679; Vol. II: pp. xxxii+811. £6 6*s*.

In a period of scientific writing in which the name of nearly every producer is associated with some highly specialized field, these two volumes of *Mathematical and Physical Papers* by Sir Joseph Larmor make a very pleasing change. The wide range of subjects here presented indicates a breadth of interest and adaptation of intuitive methods and analytical skill that reminds one of an earlier investigator at the University of Cambridge.

The set of papers seems devoid of any system except the chronological order of their original publication which extended over a period of nearly forty years. The author explains in the Preface that the suggestion was made by colleagues some twenty years ago that his papers on electrodynamics be put in book form for the Cambridge University Press but because of incomplete material and the pressure of other duties the project was not carried forward. In 1927, with the field still uncovered by "any history of progress of electrical theories toward a coherent system," the original plan still seemed feasible. For the sake of future historical interests and to preserve the progressive clarification of the writer's own outlook, the chronological order of publication was retained.

It is not easy to classify definitely the papers and their appendices because of the involved character of some, and it will perhaps suffice to say that about half of them are on electrodynamics and the others scattered over the fields of analysis, mechanics, optics, astronomy, biographical memoirs, etc.

The chief feature of the two volumes is the dynamical theory of the electrical and luminiferous medium which, with its abstracts, takes up nearly four hundred pages. This elaborate and detailed discussion goes with admirable directness into the question of rotational elements, the newly established electron, and the various ideas introduced by contemporary or earlier writers such as Stokes, Kelvin, Maxwell, Mac Cullagh, and Fresnel. It illustrates strikingly the enormous amount of study that was put, during the last part of the nineteenth century, upon this baffling subject of the ether.

The paper "On the Theory of Magnetic Influence on Spectra" has probably made Larmor's name most widely known. It is a clear analysis of the Zeeman effect in terms of the dynamics of the electron within the atom, a most noteworthy achievement in view of the newness of the idea of the electron.

Among the earlier papers is one on Hamilton's principle, which emphasizes its valuable property of reducing to a single formula an entire dynamical situation, however strange and new the system of co-ordinates may be. A later paper "On the Geometrical Method," given as a presidential address before the Society for Improvement of Geometrical Teaching, is a convincing argument for the study of geometry. It is valuable for its training in logic and the intuitive familiarity with space figures that it gives.

In this connection it is appropriate to note how favorably the use of conceptual models for any theory is considered throughout the whole set of papers. They are regarded as invaluable checks on the consistency of sets of mathematical equations which in some periods of the history of electrodynamical theory have been much underestimated. The author cites how Maxwell's equations were supported by such models and quotes Lord Kelvin in this connection.

Paper No. 89 is a scholarly address to the London Mathematical Scciety when for a few paragraphs the speaker deplores the neglect of geometrical methods and the tendency to specialization and then proceeds to the principal part, a discussion of some fifteen thousand words on "The Fourier Harmonic Analysis, Its Practical Scope with Optical Illustration."

In one of the three biographical memoirs comes a very fine tribute to J. Willard Gibbs for "his tremendous power through arguments in graphical or geometrical form to attain complete generalization as he did in thermodynamics."

While a true appreciation of the range of subjects is not possible without a complete list of titles, the following partial list will serve as a suggestion:

On the Period of the Earth's Free Eulerian Precession
Methods of Mathematical Physics
Note on Pressure Displacement of Spectral Lines
Physical Aspect of Atomic Theory
Can Convection in the Ether Be Detected Electrically?
On the Mathematical Expression of the Principle of Huyghens
Irregularities in the Earth's Rotation

Periodic Disturbance of Level Arising from Load of Neighboring Ocean Tides
Why Wireless Rays Can Bend around Earth: An Answer to Lord Rayleigh's Question
Mechanics of the Ascent of Sap in Trees
What Determines the Resistance and Tilt of an Aeroplane
John Michell, His Contribution to Astronomy
Time and Space of an Astronomical Observer
Mind, Nature, and Atomism
Synoptic View of a Physical Universe Optically Apprehended
Etc.

The number of different journals and publications in which the papers originally appeared is quite significant of the breadth of the author's interest and the high regard in which his communications have been held. The list would include among others the publications of the Royal Society, the Royal Society of Edinburgh, the Cambridge Philosophical Society, the London Mathematical Society, the Manchester Literary and Philosophical Society; the *Philosophical Magazine;* and the *Astrophysical Journal.*

Although it was the original intention to make the collection entirely complete, certain extensive omissions had at the last moment to be made. These consisted of a series of articles written for the *Encyclopaedia Britannica*, biographical notes and articles on relativity.

The reading of the papers is greatly facilitated by many marginal notes by the author. Extensive footnotes and appendices are included, but the attempt has been made throughout to preserve the original wording, and later notes, additions, and corrections are clearly indicated. Very few illustrations have been used, and what there are consist of the simplest sort of diagrams.

The physical sciences are advancing so rapidly and the significance of any step is so subject to its absorption in some larger and more recent one that it sometimes seems that any production is valuable mostly for historical purposes. In this respect at least these two volumes make a most valuable addition to the literature of mathematical physics.

F. E. Carr